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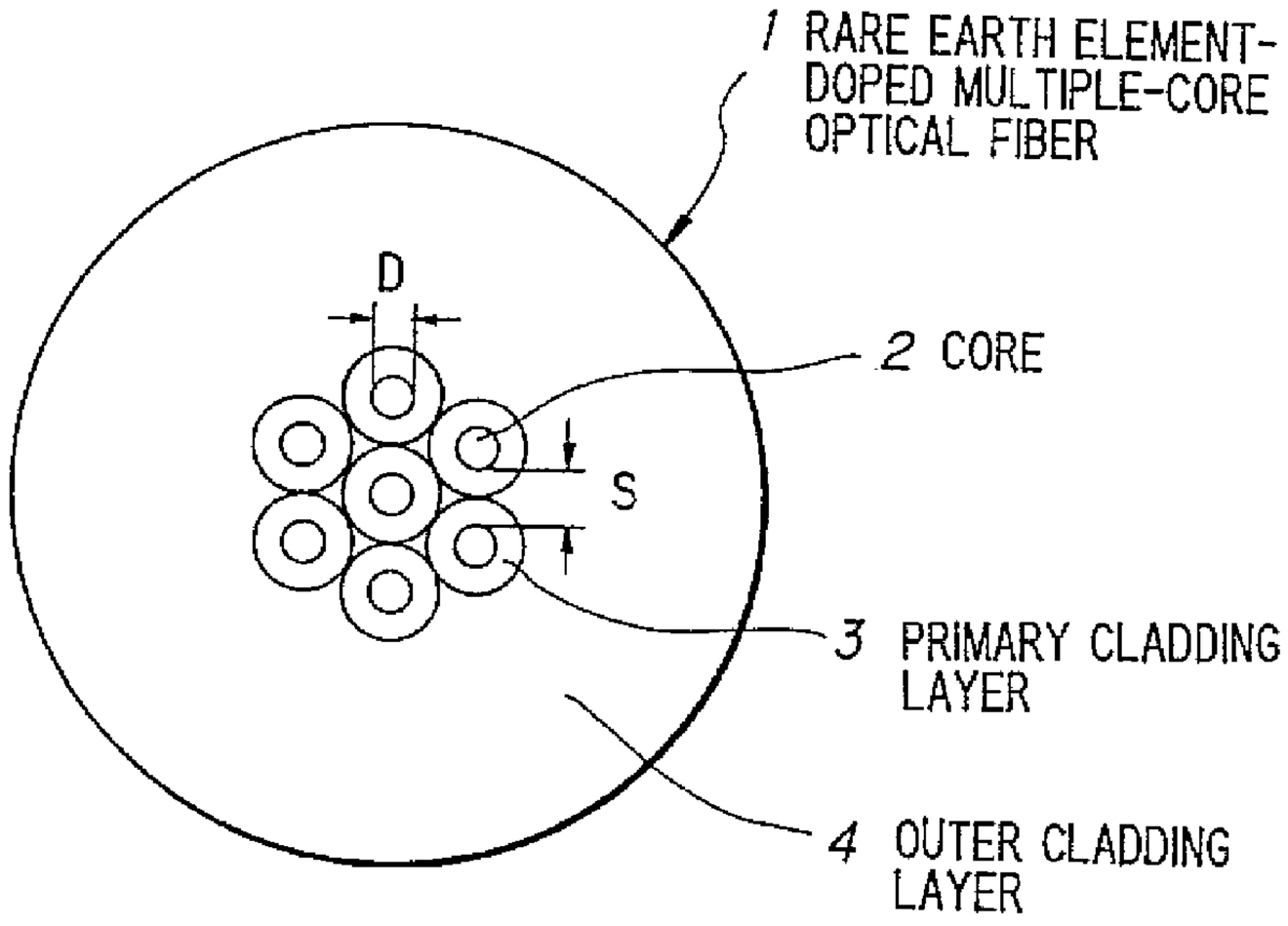


(57) Abrégé/Abstract:
A rare earth element-doped multiple-core optical fiber has an outer cladding layer and a plurality of cores each covered with a primary cladding layer. The cores are positioned substantially on a central axis of the outer cladding layer and separated with a predetermined spacing S from each other by the primary cladding layer. The outer cladding layer is made of SiO_2, or SiO_2 to which a dopant like F, Ge, etc. is added. The primary cladding layer is made of SiO_2 doped with Er, or SiO_2 doped with Er and F together and formed to have a predetermined thickness of 1.0μm ~ 1.5μm to form the predetermined spacing S. The soot glass rods for cores and primary cladding layers are immersed in an Er-compound solution, then picked up, dried and consolidated to form Er-Al co-doped SiO_2 - GeO_2 transparent glass rods. The glass rods are inserted into a quartz tube and collapsed by heat to fabricate an optical fiber preform rod, then heated to be drawn to provide an Er-doped multiple-core optical fiber.

ABSTRACT OF THE DISCLOSURE

A rare earth element-doped multiple-core optical fiber has an outer cladding layer and a plurality of cores each covered with a primary cladding layer. The cores are positioned substantially on a central axis of the outer cladding layer and separated with a predetermined spacing S from each other by the primary cladding layer. The outer cladding layer is made of SiO_2, or SiO_2 to which a dopant like F, Ge, etc. is added. The primary cladding layer is made of SiO_2 doped with Er, or SiO_2 doped with Er and F together and formed to have a predetermined thickness of 1.0μm ~ 1.5μm to form the predetermined spacing S. The soot glass rods for cores and primary cladding layers are immersed in an Er-compound solution, then picked up, dried and consolidated to form Er-Al co-doped SiO_2 - GeO_2 transparent glass rods. The glass rods are inserted into a quartz tube and collapsed by heat to fabricate an optical fiber preform rod, then heated to be drawn to provide an Er-doped multiple-core optical fiber.

RARE EARTH ELEMENT-DOPED MULTIPLE-CORE OPTICAL FIBER AND METHOD FOR FABRICATING THE SAME

This invention relates to a rare earth element-doped optical fiber and, more particularly, to a rare earth element-doped multiple-core optical fiber having a high gain and widely flat characteristics of gain to wavelength, and a method for fabricating the same.

These days, an optical fiber amplifier using a rare earth element-doped optical fiber, which is doped with a rare earth element such as Er, Pr, Nd, etc. into a core thereof, has been developed and improved for practice. Especially, an Er-doped optical fiber amplifier, which can provide a high gain and a high saturated output power at the 1.55μm wavelength band, is expected to be applied to various optical systems. Its application to a high-speed, large-quantity, and long-distance optical transmission system using a wavelength division multiplexing transmission technique of more than several channels between 1.53μm and 1.56μm wavelength bands, and an optical CATV system, for example, has been noted. In such optical transmission systems, it is important that the Er-doped optical fiber amplifier has flat gain characteristic in such wavelength bands.

In order to realize such flat characteristics of gain to wavelength, an Er-doped multiple-core optical fiber and a method for fabricating the same have previously been proposed by the inventors. The optical fiber comprises a plurality of cores doped with rare earth elements, such as Er and Al together, and an outer cladding layer which is provided around the cores, each of which is directly covered by a primary cladding layer. For this structure, the cores can contain a much higher concentration of Al dopant than a single core of a conventional Er-doped optical fiber. Furthermore, gain of each core is to be lowered to obtain flat characteristics of gain to wavelength, then, high gain is provided by superposing all outputs thereof in addition to the flattened characteristics of gain to wavelength.

In an optical fiber amplifier using such a proposed Er-doped multiple-core optical fiber, however, the inventors have found disadvantages in that when the spacing among the cores of the optical fiber become larger, gain suddenly drops, although flat characteristics of gain to wavelength in a wavelength band of 1.53μm ~ 1.57μm are obtained.

Accordingly, it is an object of the invention to provide a rare earth element-doped multiple-core optical fiber, and a method for fabricating the same, by which gain is high and widely flat characteristics of gain to wavelength are obtained.

It is another object of the invention to provide a rare earth element-doped multiple-core optical fiber, and a method for fabricating the same, by which a lesser gain drop occurs even if the spacing among the cores becomes large.

It is another object of the invention to provide a rare earth element-doped multiple-core optical fiber, and a method for fabricating the same, by which the excitation light power becomes lower and the length of the optical fiber becomes shorter.

It is another object of the invention to provide a method for fabricating a rare earth element-doped multiple-core optical fiber, by which a rare earth element-doped multiple-core optical fiber having high gain and wide wavelength band characteristics is fabricated precisely and economically.

According to the first aspect of the invention, a rare earth element-doped multiple-core optical fiber comprises: a plurality of cores each having a refractive index of n_w doped with at least one rare earth element and Al therein; a plurality of primary cladding layers each having a refractive index of n_p ($n_p < n_w$) doped with at least one rare earth element, and covering each of the cores; and an outer cladding layer having a refractive index of n_c ($n_w > n_c$ and $n_p \leq n_c$), and covering said plurality of cores covered with the plurality of primary cladding layers; wherein the cores are positioned substantially on a central axis of the outer cladding layer, and separated with a predetermined spacing by the plurality of primary cladding layers.

According to the second aspect of the invention, a rare earth element-doped multiple-core optical fiber comprises: a plurality of cores each having a refractive index of n_w doped with at least one rare earth element and Al therein; a plurality of intermediate cladding layers each having a refractive index of n_i ($n_i < n_w$) doped with at least one rare earth element, and covering the plurality of cores; a plurality of primary cladding layers each having a refractive index of n_p ($n_p \leq n_i$ and $n_p < n_w$) doped with at least one rare earth element, and covering the plurality of intermediate cladding layers; and an outer cladding layer having a refractive index of n_c ($n_w > n_c$, $n_i \leq n_c$ and $n_p \leq n_c$), and covering the plurality of cores covered with the plurality of intermediate and primary cladding layers; wherein the plurality of cores are positioned substantially on a central axis of the outer cladding layer, and separated with a predetermined spacing by the plurality of intermediate cladding layers.

According to the third aspect of the invention, a method for fabricating a rare earth element-doped multiple-core optical fiber comprises the steps of: fabricating a plurality of soot glass rods, each of which is provided with a core containing Al and a

primary cladding layer directly covering the core; immersing the plurality of soot glass rods in a rare earth element-compound solution; picking up the plurality of soot glass rods from the solution, and drying and consolidating them to provide a plurality of rare earth element and Al co-doped transparent glass rods; inserting the plurality of co-doped transparent glass rods into a quartz tube; heating and collapsing the quartz tube thus inserted with the plurality of co-doped transparent glass rods to fabricate an optical fiber preform rod; and heating and drawing the optical fiber preform to provide a rare earth element-doped multiple-core optical fiber.

According to the fourth aspect of the invention, a method for fabricating a rare earth element-doped multiple-core optical fiber comprises the steps of: fabricating a plurality of soot glass rods, each of which is provided with a core containing Al and an intermediate cladding layer directly covering the core; immersing the plurality of soot glass rods in a rare earth element-compound solution; picking up the plurality of soot glass rods from the solution, drying and consolidating them to provide a plurality of rare earth element and Al co-doped transparent glass rods; covering each of the co-doped transparent glass rods with a primary cladding layer; inserting the plurality of co-doped transparent glass rods with the intermediate cladding layers and the primary cladding layers into a quartz tube; heating and collapsing the quartz tube to fabricate an optical fiber preform rod; and heating and drawing the optical fiber preform rod to provide a rare earth element-doped multiple-core optical fiber.

The invention will be explained in more detail in conjunction with the appended drawings, wherein:

Figure 1 is a cross-sectional view showing a rare earth element-doped multiple-core optical fiber according to the first preferred embodiment of the invention,

Figure 2 is a cross-sectional view showing a rare earth element-doped multiple-core optical fiber according to the second preferred embodiment of the invention,

Figure 3 is a flow chart showing a method for fabricating a rare earth element-doped multiple-core optical fiber which was formerly proposed by the inventors,

Figure 4 is a graph showing the characteristics of gain to core spacing for rare earth element-doped multiple-core optical fibers according to the invention and a rare earth element-doped multiple-core optical fiber which was formerly proposed by the inventors,

Figure 5 is a structural view showing a rare earth element-doped multiple-core optical fiber amplifier,

Figure 6 represents (a) sectional views of two types of cores, each covered by a primary cladding layer, of a rare earth element-doped multiple-core optical fiber according to the first preferred embodiment of the invention, (b) profiles of the respective refractive indices, and (c) profiles of the respective Er concentrations,

Figure 7 represents (a) sectional views of two types of cores, each covered by an intermediate cladding layer and a primary cladding layer, of a rare earth element-doped multiple-core optical fiber according to the second preferred embodiment of the invention, (b) profiles of the respective refractive indices, and (c) profiles of the respective Er concentrations,

Figure 8 is a flow chart showing a method for fabricating a rare earth element-doped multiple-core optical fiber according to the first preferred embodiment of the invention,

Figure 9 is a flow chart showing a method for fabricating a rare earth element-doped multiple-core optical fiber according to the second preferred embodiment of the invention, and

Figure 10 is a flow chart showing a method for fabricating a rare earth element-doped multiple-core optical fiber according to the second preferred embodiment of the invention.

Before explaining a rare earth element-doped multiple-core optical fiber in the first preferred embodiment, the aforementioned rare earth element-doped multiple-core optical fiber, formerly proposed by the inventors, and a method for fabricating the same will be explained with reference to Figure 1.

The Er-doped optical fiber 1 comprises a plurality of cores 2 (seven cores in this case) doped with Er and Al together, and an outer cladding layer 4 which is provided around the cores 2, each of which is directly covered by a primary cladding layer 3.

Figure 5 shows a rare-earth element-doped multiple-core optical fiber amplifier using such an optical fiber, which comprises a certain length of a rare-earth element-doped multiple-core optical fiber 1, light sources (not shown) for emitting excitation lights 11-1 and 11-2, to be injected through WDM couplers 8-1 and 8-2 into the optical fiber 1 at front and rear stages, respectively.

In operation, the excitation lights 11-1 and 11-2 are coupled with single mode optical fibers 9-1 and 9-2 through WDM couplers 8-1 and 8-2, then absorbed in the optical fiber 1 inherently to amplify a signal light 10-1 transmitted through the optical fiber 1 to

obtain an amplified signal light 10-2. Optical isolators 7-1 and 7-2 are preferably used for suppressing a retrograde signal light of the amplified signal light 10-2.

Next, now referring to Figure 3, a method for fabricating an Er-doped multiple-core optical fiber proposed by the inventors will be explained below.

SiO_2 -GeO_2 -Al_2O_3 composite soot glass rods are fabricated by an ordinary fabrication process such as VAD method (at step A). Next, the soot glass rods are immersed in an Er-compound solution (at step B). Then the soot glass rods are picked up from the solution, dried and consolidated by an electrical heater to obtain Er-Al co-doped SiO_2 -GeO_2 transparent glass rods (at step C). After that, each of the rods is covered by a primary cladding layer by an ordinary fabrication process such as outer CVD method (at step D), the plurality of rods with the primary cladding layers are inserted into a quartz tube (at step E), and the quartz tube is heated by oxyhydrogen-burner and collapsed to fabricate an optical fiber preform rod (at step F). Finally, the optical fiber preform is moved into an electric heater at a predetermined speed to be heated, an end of the fused rod is drawn out of the heater and wound around a drum to provide an Er-doped multiple-core optical fiber (at step G).

According to such structure of the Er-doped multiple-core optical fiber, high gain is obtained as well as the flat characteristics of gain to wavelength. The reasons for this will be explained in more detail by the following.

First, the cores can contain a much higher concentration of Al dopant than a single core in a conventional Er-doped optical fiber. Second, for this structure, though a gain of each core is to be lowered to obtain flat characteristics of gain to wavelength, then a high gain is provided by superposing all outputs thereof in addition to the flattened characteristics of gain to wavelength. The conventional characteristics of gain to wavelength show that injected excitation light power is lowered, the peak of gain observed near 1.535μm wavelength decreases, and gain relative to wavelength becomes flat gradually. As the excitation light power becomes lower, a right hand increasing tendency is observed, that is to say, the gain at a shorter wavelength band (1.53μm wavelength side) becomes lower, and the gain at a longer wavelength band (1.56μm wavelength side) becomes high. If the excitation light power is drastically reduced, the gain is too low to be used as an optical fiber amplifier. The Er-doped multiple-core optical fiber proposed by the inventors utilizes such principle actively. If an outer diameter D of the core 2, and a spacing S among the cores 2 is optimized so that an excitation light and a signal light are almost equally distributed and transmitted in each core, a gain of each core is low but a flat

gain relative to wavelength is obtained. The signal lights, being transmitted through a certain length of the fiber, are amplified in each core, respectively, and superposed as an output signal. As a result, the gain is high, and the characteristics of gain to wavelength are flattened.

In such Er-doped multiple-core optical fibers, however, there is disadvantage as described below. The characteristics of gain to core spacing for optical fiber amplifiers using a variety of Er-doped multiple-core optical fibers have been measured. The result for an optical fiber amplifier which uses the optical fiber formerly proposed by the inventors having a core of approximately 2μm diameter is indicated as "PRIOR EXAMPLE" in Figure 4. The result shows that as the core spacing S(μm) is increased, the gain G (dB) decreases drastically, as described before, although the flat characteristics of gain to wavelength become wider in 1.53μm ~ 1.57μm wavelength bands.

The reason for this is that optical isolators 7-1 and 7-2, and WDM couplers 8-1 and 8-2 are made from the same fiber as the single mode optical fibers 9-1 and 9-2, each of which is provided with, for example, a core of 10μm diameter, a cladding layer of 125μm diameter, and a specific refractive index difference of 0.3%. If the single mode optical fibers 9-1 and 9-2 are connected to both ends of the rare earth element-doped multiple-core optical fiber, a part of the signal lights and the excitation lights are transmitted through the primary cladding layer 3, in addition to being transmitted through the seven cores 2 co-doped with a rare earth element Er and Al. As a result, the power of such partial lights transmitted through each primary cladding layer 3 increases, as the core spacing S becomes larger. The inventors have studied this phenomenon and have found that no rare earth element is doped in each primary cladding layer to contribute to amplifying the signal light, so that the gain decreases as the core spacing S becomes larger.

Next, a rare earth element-doped optical fiber in the first preferred embodiment according to the invention will be explained with reference to Figure 1.

In the first preferred embodiment, a rare earth element-doped multiple-core optical fiber 1 is provided with an outer cladding layer 4 having an approximately circular cross-section, and seven cores 2, each having a predetermined diameter D, being positioned substantially along the central axis of the cladding layer so as to be separated with a predetermined spacing S from each other by a primary cladding layer 3. The outer cladding layer 4 is made of SiO_2, or SiO_2 added with a dopant, such as F, Ge, etc., for controlling the refractive index and is generally formed to have an outer diameter of approximately 125μm. The primary cladding layer 3, which directly covers the core 2, is

made of SiO_2 doped with Er, or SiO_2 doped with Er and F together, and formed to have a predetermined thickness so as to separate the cores 2 from each other with a core spacing S of 1.0μm ~ 1.5μm. The refractive index n_p of the primary cladding layer 3 is to be lower than the refractive index n_w of the core 2, and is equal to or lower than the refractive index n_c of the outer cladding layer 4. It is preferable that the primary cladding layer 3 contains at least 50 ppm of Er, and a profile of Er concentration, which will be explained later, may be varied along the primary cladding layer thickness direction, or may be constant. Regarding the concentration of Er dopant in the primary cladding layer, the higher it is, the more the Er dopant contributes to the amplification of the signal light. However, the upper limit of Er dopant concentration should not exceed the Er concentration in the core 2.

Figure 2 shows a rare earth element-doped optical fiber in the second preferred embodiment according to the invention, wherein like parts are indicated by like reference numerals as used in Figure 1. A rare earth element-doped optical fiber in the second preferred embodiment is provided with cores 2 each doped with Er and Al together, being directly covered by an intermediate cladding layer 5, and a primary cladding layer 6 containing no rare earth element dopant to cover the intermediate cladding layer 5 directly. The refractive index n_p of the primary cladding layer 6 is to be lower than a refractive index n_w of the core 2, but equal to or lower than a refractive index n_c of the outer cladding layer 4, and equal to or higher than the refractive index n_i of the intermediate cladding layer 5. The material used as the primary cladding layer 6 is different from that in the first preferred embodiment, which may include SiO_2 without Er dopant, or SiO_2 doped with F, B, or Ge. The thickness thereof is predetermined to be much thinner than that of the intermediate cladding layer 5. The intermediate cladding layer 5 is made of SiO_2 doped with at least 50 ppm of Er, which may additionally contain F, so as to amplify a signal light transmitted through the layer. In the second preferred embodiment, a spacing S among the cores 2 is adjusted by controlling the thickness of the intermediate cladding layer 6. Regarding the concentration of Er dopant therein, the higher it is, the more the Er dopant contributes to amplifying the signal light, but the upper concentration limit of Er dopant is determined not to exceed the Er concentration in the core 2.

In the first and second preferred embodiments, the core diameter D is determined as $1 \leq D < 3\mu m$ so that the combined multiple core diameter is substantially equal to a mode-field diameter of the single mode optical fibers to be connected thereto, which is approximately 10μm. The specific refractive index difference between the cores and the outer cladding layer, or between the cores and the primary cladding layers is at

least 1%. A higher specific refractive index difference is preferable for a high gain amplification, and a maximum value may be approximately 2.5%, which is obtained by adding F into the outer cladding layer or the primary cladding layer. The material used as the cores may include Er-Al co-doped SiO_2, Er-Al co-doped SiO_2 -GeO_2 -P_2O_5, Er-Al co-doped SiO_2 -P_2O_5, etc. and the concentration of Er dopant therein is at least 200 ppm and may increase to approximately 1500 ppm. A higher concentration of Er is preferable for obtaining a high gain amplification and flat characteristics of gain to wavelength. It is also preferable that the concentration of Al dopant in the cores is at least 7000 ppm and may increase to approximately 3.5% for obtaining flat characteristics of gain to wavelength. Besides Er, at least one other rare earth element such as Pr, Nd, Yb, Sm, Tm, Ce, etc. may be doped with Al into the cores.

Figure 6 shows two types, (A) and (B), of cores covered by primary cladding layers in a rare earth element-doped multiple-core optical fiber according to the first preferred embodiment of the invention, wherein the enlarged cross-sectional views, refractive index profiles, and Er concentration profiles for types (A) and (B) are indicated by (a), (b), and (c), respectively. In type (A), the core 2 has a constant refractive index higher than that of a primary cladding layer 3. The Er concentration therein has a quasi-step profile. In type (B), the core 2 has a graded refractive index and the Er concentration therein has a nearly Gaussian distribution profile. Regarding the specific refractive index differences between cores 2 and primary cladding layers 3, approximately the same values may be obtained in type (A) and (B) by increasing the maximum value of refractive index in the core of type (B).

Figure 7 shows two types, (A) and (B), of cores covered by primary cladding layers of a rare earth element-doped multiple-core optical fiber according to the second preferred embodiment of the invention. In type (A), core 2 has a constant refractive index higher than those of the intermediate cladding layer 5 and the primary cladding layer 6, then, it has a step index profile. The Er concentration therein has a quasi-step profile. In type (B), core 2 has a constant refractive index, and the intermediate cladding layer 5 has a refractive index lower than that of the core 2 and the primary cladding layer 6 to provide an approximately W-shaped refractive index profile. The Er concentration therein has a nearly Gaussian distribution profile.

In the invention, refractive indices and Er concentration profiles are adjusted by controlling conditions such as time for immersing a soot glass rod in an Er-compound

solution, Er concentration of the solution, time for drying the soot glass rod after the immersion, time and temperature for consolidation, etc.

Next, a method for fabricating a rare earth element-doped multiple-core optical fiber according to the first preferred embodiment of the invention will be explained with reference to Figure 8. Soot glass rods comprising SiO_2 -GeO_2 -Al_2O_3 for cores, and SiO_2 or SiO_2 doped with F for primary cladding layers are fabricated by an All-synthetic process such as VAD method (at step A). Next, the soot glass rods are immersed in an Er-compound solution (at step B). In this process, the immersion time is controlled so as to provide certain Er concentration profiles thereof, such as a step or a Gaussian distribution as shown in Figure 6. Then the soot glass rods are picked up from the solution, dried and consolidated by an electrical heater to obtain Er-Al co-doped SiO_2 -GeO_2 transparent glass rods with primary cladding layers (at step C). After that, a plurality of rods with primary cladding layers are inserted into a quartz tube (at step D). The quartz tube is evacuated, heated by oxyhydrogen-burner from one end to another, and collapsed to fabricate an optical fiber preform rod (at step E). Finally, the optical fiber preform rod is moved into an electric heater at a predetermined speed to be heated, an end of the fused rod is drawn out of the heater and wound around a drum to provide an Er-doped multiple-core optical fiber (at step F).

Instead of step A, soot glass rods may be fabricated by two separate steps, that is to say, fabricating soot glass rods for Al-containing cores, such as SiO_2 -GeO_2 -Al_2O_3 cores (at step A′), then producing primary cladding layers of soot glass thin layers around the soot glass rods (at step A"), as encircled by a broken line in Figure 8. Both steps may be processed by VAD method, and soot glass rods are fabricated by using two flame-hydrolysis-burners, which are positioned with a predetermined distance on the picking-up direction of the rods to provide an upper burner and a lower burner. Soot glass rods for cores and soot glass thin layers for primary cladding layers are produced by the upper and lower burners, respectively.

Next, a method for fabricating a rare earth element-doped multiple-core optical fiber according to the second preferred embodiment of the invention will be explained in Figure 9. Soot glass rods comprising SiO_2 -GeO_2 -Al_2O_3 for cores and SiO_2 for intermediate cladding layers are fabricated by an All-synthetic process such as VAD method (at step A). Next, the soot glass rods are immersed in an Er-compound solution (at step B). Then the soot glass rods are picked up, dried and consolidated by an electrical heater to obtain Er-Al co-doped SiO_2 -GeO_2 transparent glass rods with intermediate

cladding layers (at step C). After that, each of the rods is covered by a primary cladding layer in an ordinary fabrication process such as outer CVD method (at step D). After that, in the same manner as in the method for fabricating the optical fiber in the first preferred embodiment, the plurality of rods are inserted into a quartz tube (at step E). The tube is heated and collapsed to fabricate an optical fiber preform rod (at step F), then, the optical fiber preform rod is heated and drawn to provide an Er-doped multiple-core optical fiber (at step G). Besides step A, in the same manner as in the method for fabricating the optical fiber in the first preferred embodiment, soot glass rods may be fabricated by two separate steps, as shown encircled by a broken line in Figure 9. In this case, soot glass rods for Al-containing cores are fabricated (at step A′), and intermediate cladding layers of soot glass thin layers are produced around the soot glass rods (at step A"). Both steps may be processed by VAD method.

Another method for fabricating a rare earth element-doped multiple-core optical fiber according to the second preferred embodiment of the invention will be explained in Figure 10. Especially in this case, intermediate cladding layers are made of F-doped SiO_2 (at step A). A step-shaped refractive index profile, which is shown in Figure 7(A), may be obtained by using a material such as F-doped SiO_2 for both primary cladding layers and the outer cladding layer, and a W-shaped refractive index profile, which is shown in Figure 7(B), may be obtained by using SiO_2 or Ge-doped SiO_2.

A variety of Er-doped multiple-core optical fibers are fabricated in the invention by the methods described before, and the characteristics of gain to core spacing are measured for optical fiber amplifiers. TABLE 1 shows structural parameters of such Er-Al co-doped multiple-core optical fibers according to the invention, together with an Er-Al co-doped multiple-core optical fiber which was formerly proposed by the inventors for comparison.

TABLE 1

		PRIOR EXAMPLE	EXAMPLE 1 (FIG.6(A))	EXAMPLE 2 (FIG.6(B))	EXAMPLE 3 (FIG.7(A))	EXAMPLE 4 (FIG.7(B))
Er-CONCENTRATION (ppm)		400	400	400	400	400
Al-CONCENTRATION (ppm)		8500	8500	8500	8500	8500
CORE	REFRACTIVE INDEX	1.4795	1.4795	1.4807	1.4795	1.4795
	OUTER DIAMETER	1.95 μm	1.95 μm	1.95 μm	1.95 μm	1.95 μm
INTER-MEDIATE CLADDING LAYER	REFRACTIVE INDEX	-	-	-	1.458	1.447 (F-doped)
	THICKNESS	-	-	-	0.35 μm	0.35 μm
PRIMARY CLADDING LAYER	REFRACTIVE INDEX	1.458	1.458	1.458	1.458	1.462 (Ge-doped)
	THICKNESS	0.5 μm	0.5 μm	0.5 μm	0.15 μm	0.15 μm
OUTER CLADDING LAYER	REFRACTIVE INDEX	1.458	1.458	1.458	1.458	1.462 (Ge-doped)
	OUTER DIAMETER	125 μm	125 μm	125 μm	125 μm	125 μm

The results are shown in Figure 4, wherein a solid line is obtained for "EXAMPLE 1" in TABLE 1, a one-dotted line for the "EXAMPLE 2", a two-dotted line for the "EXAMPLE 3", and broken lines for the "EXAMPLE 4" and the "PRIOR EXAMPLE" are obtained, respectively. As the core spacing S is increased, a gain is drastically dropped for the "PRIOR EXAMPLE". On the contrary, gains are high and slight decreases are observed in the respective examples of the invention. For example, in the Er-Al co-doped multiple-core optical fiber amplifier using the "EXAMPLE 1" fiber, a gain of 35 dB and a wavelength band width where gain drops by 1 dB from its maximum value ("1 dB band width") of 26 nm at an input signal light power of -17 dBm are obtained. In addition to that, a gain of 29 dB and a 1 dB band width of 51 nm at an input signal light power of -10 dBm are obtained. This band width is 1.5 to 2.2 times as wide as that obtained by the conventional Er-doped optical fiber amplifiers.

In the invention, a rare earth element-doped multiple-core optical fiber is not limited to an optical fiber having seven cores as shown in Figures 1 and 2, but may include optical fibers having a different number of cores such as three, nine, and nineteen cores.

As well explained above, the invention provides advantages set out below.

(1) A reduction in gain drop occurs even if the spacing among the cores becomes larger. Therefore, in an optical fiber amplifier, gain is kept high and widely flat characteristics of gain to wavelength are obtained.

(2) The excitation light power is used effectively. Therefore, the power can be lower and a length of the optical fiber can be shorter.

(3) A rare earth element-doped multiple-core optical fiber having high gain and wide wavelength band characteristics is fabricated precisely and economically.

Although the invention has been described with respect to specific embodiments for complete and clear disclosure, the appended claims are not to be thus limited but are to be construed as embodying all modifications and alternative constructions that may occur to one skilled in the art which fairly fall within the basic teachings herein set forth.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A rare earth element-doped multiple-core optical fiber, comprising:

a plurality of cores each having a refractive index of n_w doped with at least one rare earth element and Al therein;

a plurality of primary cladding layers each having a refractive index of n_p ($n_p < n_w$) doped with at least one rare earth element, and covering each of said cores; and

an outer cladding layer having a refractive index of n_c ($n_w > n_c$ and $n_p \leq n_c$), and covering said plurality of cores covered with said plurality of primary cladding layers;

wherein said cores are positioned substantially on a central axis of said outer cladding layer, and separated with a predetermined spacing by said plurality of primary cladding layers.

2. A rare earth element-doped multiple-core optical fiber according to claim 1, wherein the number of said plurality of cores is seven, said predetermined spacing is 1.0 to 1.5μm, a diameter of said outer cladding layer is 125μm, and differences between specific refractive indices of said plurality of cores and said outer cladding layer, and between those of said plurality of cores and said plurality of primary cladding layers are each at least 1%.

3. A rare earth element-doped multiple-core optical fiber according to claim 1, wherein each of said plurality of cores is doped with a concentration of at least 200 ppm of said rare earth element and a concentration of at least 7000 ppm of Al; and

each of said plurality of primary cladding layers is doped with a concentration of at least 50 ppm of said rare earth element.

4. A rare earth element-doped multiple-core optical fiber according to claim 1, wherein the concentration of said rare earth element in each of said plurality of cores is distributed so as to decline along its radial direction.

5. A rare earth element-doped multiple-core optical fiber according to claim 1, wherein said rare earth element is Er.

6. A rare earth element-doped multiple-core optical fiber, comprising:

a plurality of cores each having a refractive index of n_w doped with at least one rare earth element and Al therein;

a plurality of intermediate cladding layers each having a refractive index of n_i ($n_i < n_w$) doped with at least one rare earth element, and covering said plurality of cores;

a plurality of primary cladding layers each having a refractive index of n_p ($n_p \leq n_i$ and $n_p < n_w$) doped with at least one rare earth element, and covering said plurality of intermediate cladding layers; and

an outer cladding layer having a refractive index of n_c ($n_w > n_c$ $n_i \leq n_c$ and $n_p \leq n_c$), and covering said plurality of cores covered with said plurality of intermediate and primary cladding layers;

wherein said plurality of cores are positioned substantially on a central axis of said outer cladding layer, and separated with a predetermined spacing by said plurality of intermediate cladding layers.

7. A rare earth element-doped multiple-core optical fiber according to claim 6, wherein the number of said plurality of cores is seven, said predetermined spacing is 1.0 to 1.5μm, the diameter of said outer cladding layer is 125μm, and differences between specific refractive indices of said plurality of cores and said outer cladding layer, and between those of said plurality of cores and said plurality of primary cladding layers are each at least 1%.

8. A rare earth element-doped multiple-core optical fiber according to claim 6, wherein each of said plurality of cores is doped with a concentration of at least 200 ppm of said rare earth element and a concentration of at least 7000 ppm of Al; and

each of said plurality of intermediate cladding layers is doped with a concentration of at least 50 ppm of said rare earth element.

9. A rare earth element-doped multiple-core optical fiber according to claim 6, wherein the concentration of said rare earth element in each of said plurality of cores is distributed so as to decline along its radial direction.

10. A rare earth element-doped multiple-core optical fiber according to claim 6, wherein each of said plurality of intermediate cladding layers is doped with said rare

earth element and F together so as to provide a lower refractive index thereof than said plurality of primary cladding layers and said outer cladding layer.

11. A rare earth element-doped multiple-core optical fiber according to claim 6, wherein said rare earth element is Er.

12. A method for fabricating a rare earth element-doped multiple-core optical fiber, comprising the steps of:

fabricating a plurality of soot glass rods, each of which is provided with a core containing Al and a primary cladding layer directly covering said core;

immersing said plurality of soot glass rods in a rare earth element-compound solution; picking up said plurality of soot glass rods from said solution, and drying and consolidating them to provide a plurality of rare earth element and Al co-doped transparent glass rods; inserting said plurality of co-doped transparent glass rods into a quartz tube;

heating and collapsing said quartz tube thus inserted with said plurality of co-doped transparent glass rods to fabricate an optical fiber preform rod; and

heating and drawing said optical fiber preform to provide a rare earth element-doped multiple-core optical fiber.

13. A method for fabricating a rare earth element-doped multiple-core optical fiber, comprising the steps of:

fabricating a plurality of soot glass rods for cores each containing Al;

producing a primary cladding layer of soot glass thin layer around each of said soot glass rods; immersing said soot glass rods each having said soot glass thin layer in a rare earth element-compound solution; picking up said soot glass rods from said solution, and drying and consolidating them to provide a plurality of co-doped rare earth element-Al co-doped transparent glass rods;

inserting said plurality of co-doped transparent glass rods into a quartz tube;

heating and collapsing said quartz tube thus inserted with said plurality of co-doped rare earth element-Al co-doped transparent glass rods to fabricate an optical fiber preform rod; and heating and drawing said optical fiber preform rod to provide a rare earth element-doped multiple-core optical fiber.

14. A method for fabricating a rare earth element-doped multiple-core optical fiber, comprising the steps of:

fabricating a plurality of soot glass rods, each of which is provided with a core containing Al and an intermediate cladding layer directly covering said core;

immersing said plurality of soot glass rods in a rare earth element-compound solution;

picking up said plurality of soot glass rods from said solution, drying and consolidating them to provide a plurality of rare earth element and Al co-doped transparent glass rods;

covering each of said co-doped transparent glass rods with a primary cladding layer;

inserting said plurality of co-doped transparent glass rods each having said intermediate cladding layer and said primary cladding layer into a quartz tube;

heating and collapsing said quartz tube to fabricate an optical fiber preform rod; and

heating and drawing said optical fiber preform rod to provide a rare earth element-doped multiple-core optical fiber.

15. A method for fabricating a rare earth element-doped multiple-core optical fiber, comprising the steps of:

fabricating a plurality of soot glass rods for cores containing Al;

producing an intermediate cladding layer of soot glass thin layer around each of said soot glass rods;

immersing said plurality of soot glass rods each having said soot glass thin layer in a rare earth element-compound solution;

picking up said plurality of soot glass rods from said solution, drying and consolidating them to provide rare earth element and Al co-doped transparent glass rods;

covering each of said plurality of glass rods with a primary cladding layer;

inserting said plurality of rods each having said intermediate cladding layer and said primary cladding layer into a quartz tube;

heating and collapsing said quartz tube to fabricate an optical fiber preform rod; and

heating and drawing said optical fiber preform rod to provide a rare earth element-doped multiple-core optical fiber.

FIG. 1

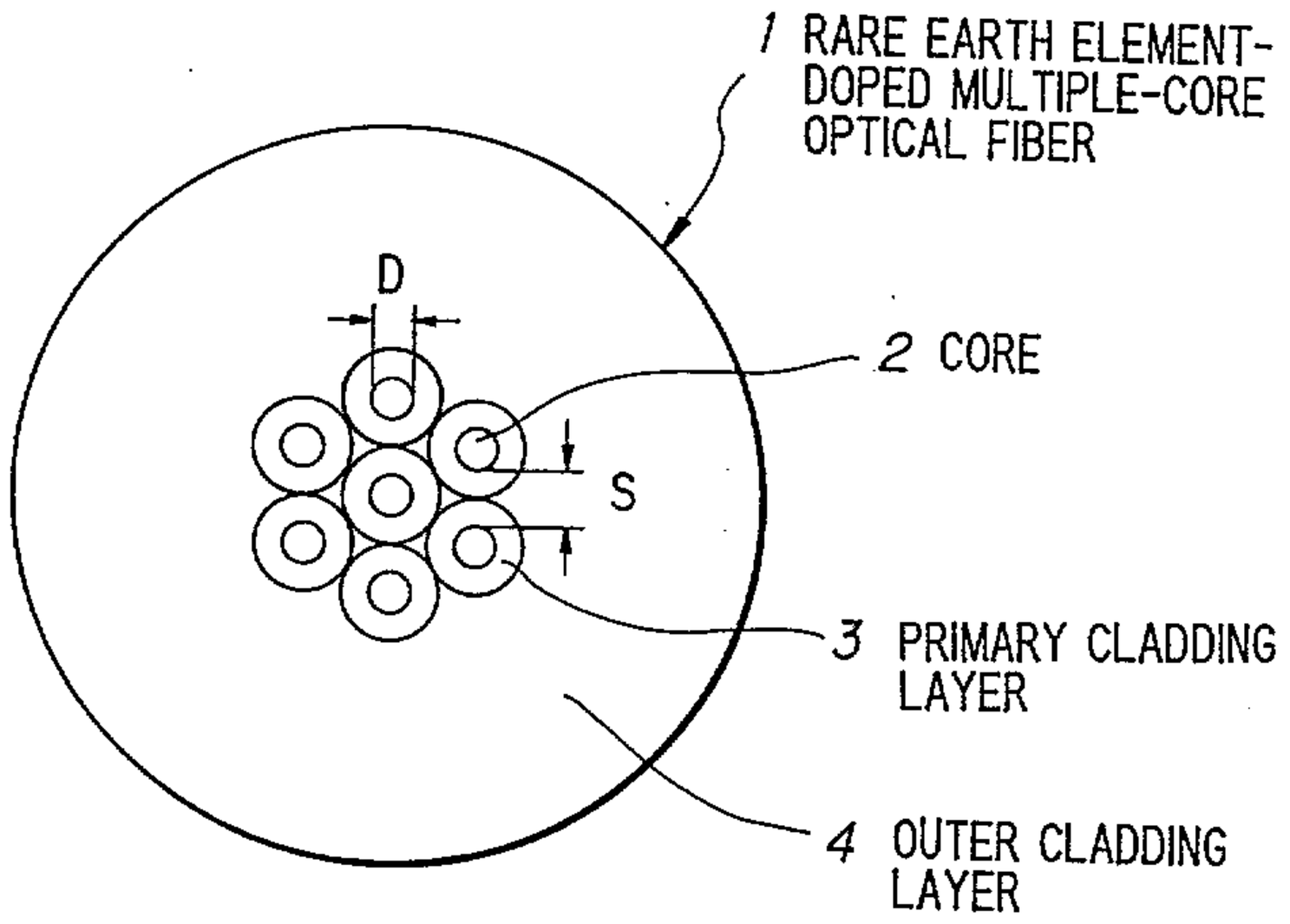

1 RARE EARTH ELEMENT-DOPED MULTIPLE-CORE OPTICAL FIBER
D
2 CORE
S
3 PRIMARY CLADDING LAYER
4 OUTER CLADDING LAYER

FIG.2

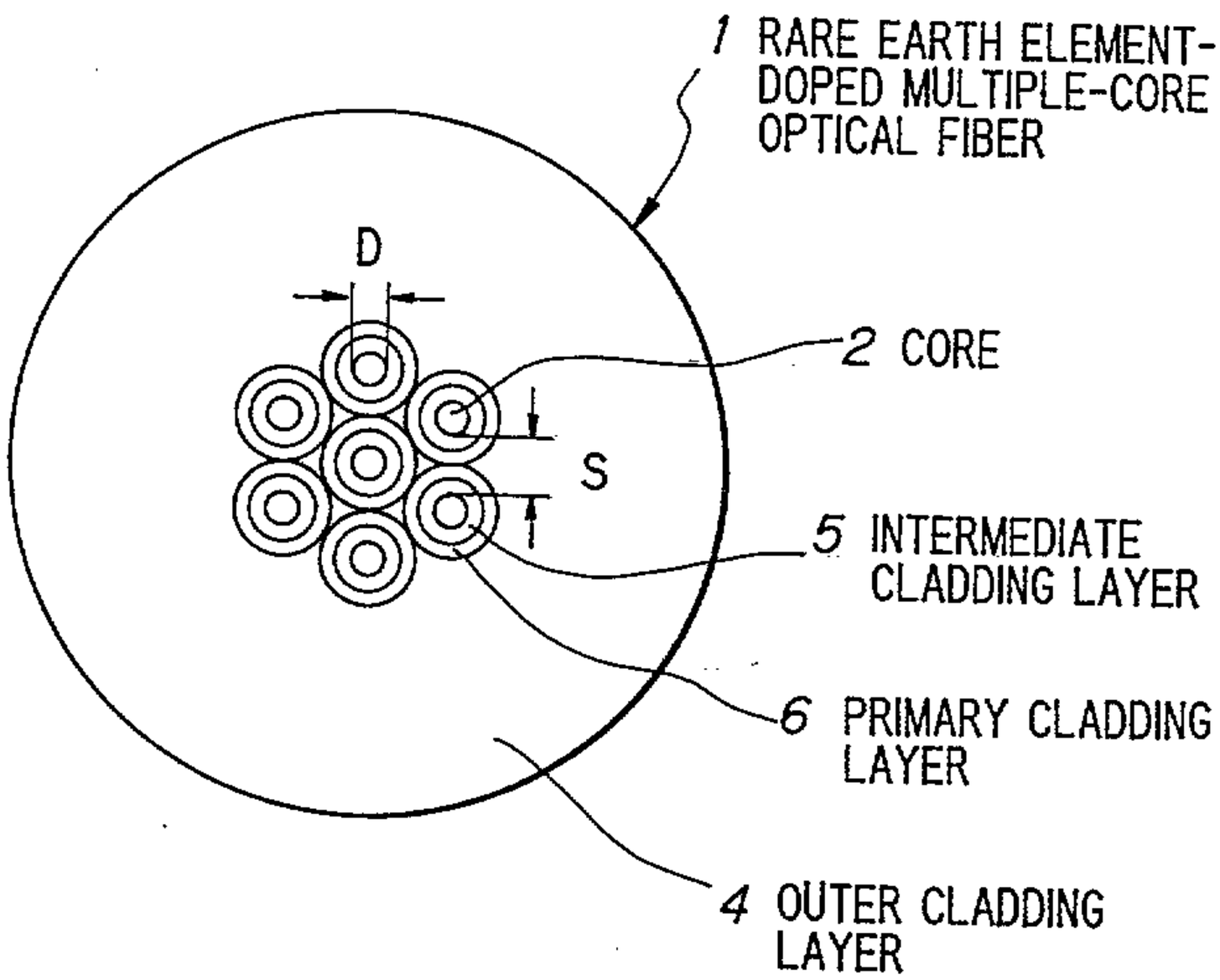

1 RARE EARTH ELEMENT-DOPED MULTIPLE-CORE OPTICAL FIBER
D
2 CORE
S
5 INTERMEDIATE CLADDING LAYER
6 PRIMARY CLADDING LAYER
4 OUTER CLADDING LAYER

FIG.3

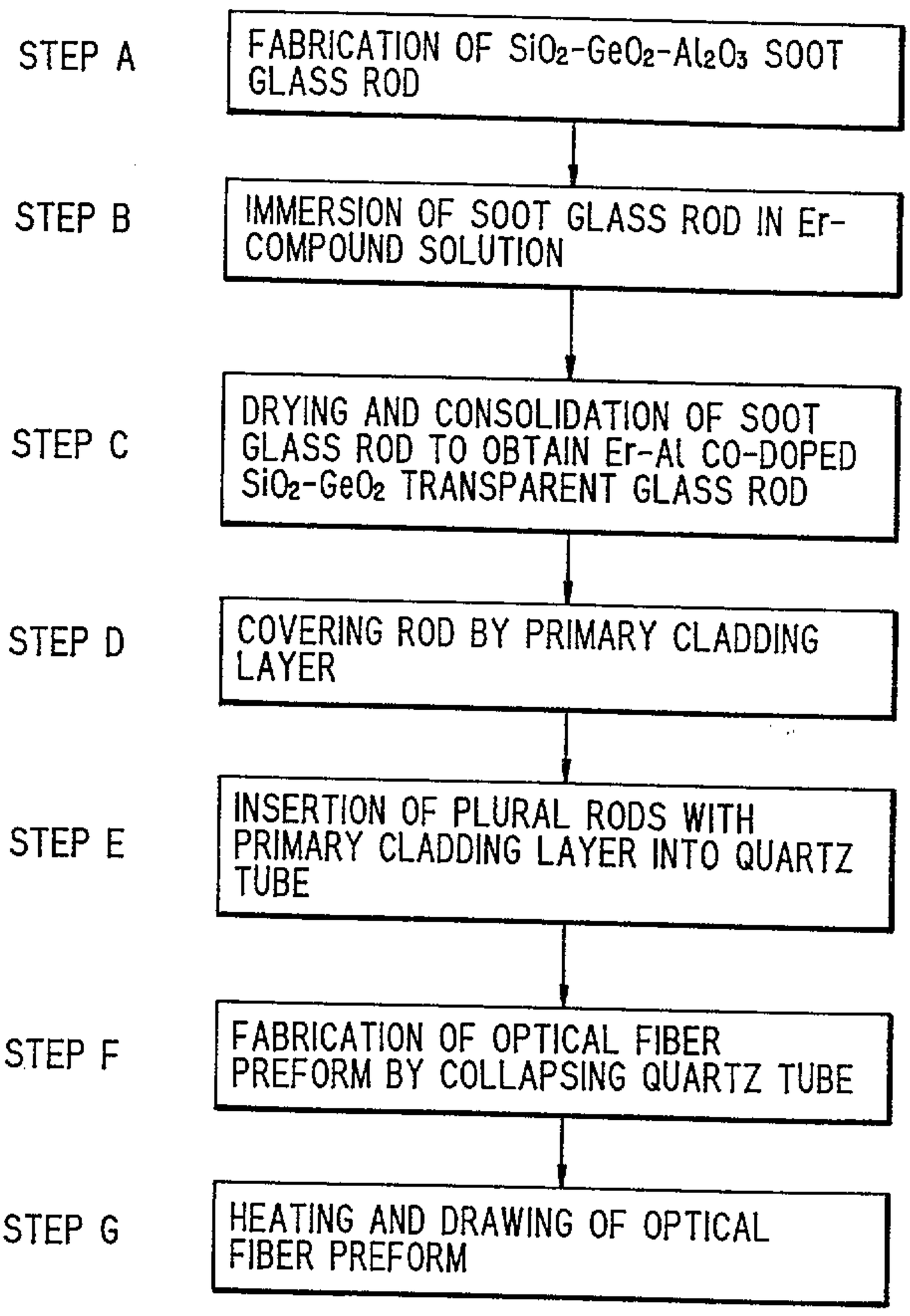

STEP A
FABRICATION OF SiO_2-GeO_2-Al_2O_3 SOOT GLASS ROD
STEP B
IMMERSION OF SOOT GLASS ROD IN Er-COMPOUND SOLUTION
STEP C
DRYING AND CONSOLIDATION OF SOOT GLASS ROD TO OBTAIN Er-Al CO-DOPED SiO_2-GeO_2 TRANSPARENT GLASS ROD
STEP D
COVERING ROD BY PRIMARY CLADDING LAYER
STEP E
INSERTION OF PLURAL RODS WITH PRIMARY CLADDING LAYER INTO QUARTZ TUBE
STEP F
FABRICATION OF OPTICAL FIBER PREFORM BY COLLAPSING QUARTZ TUBE
STEP G
HEATING AND DRAWING OF OPTICAL FIBER PREFORM

FIG. 4

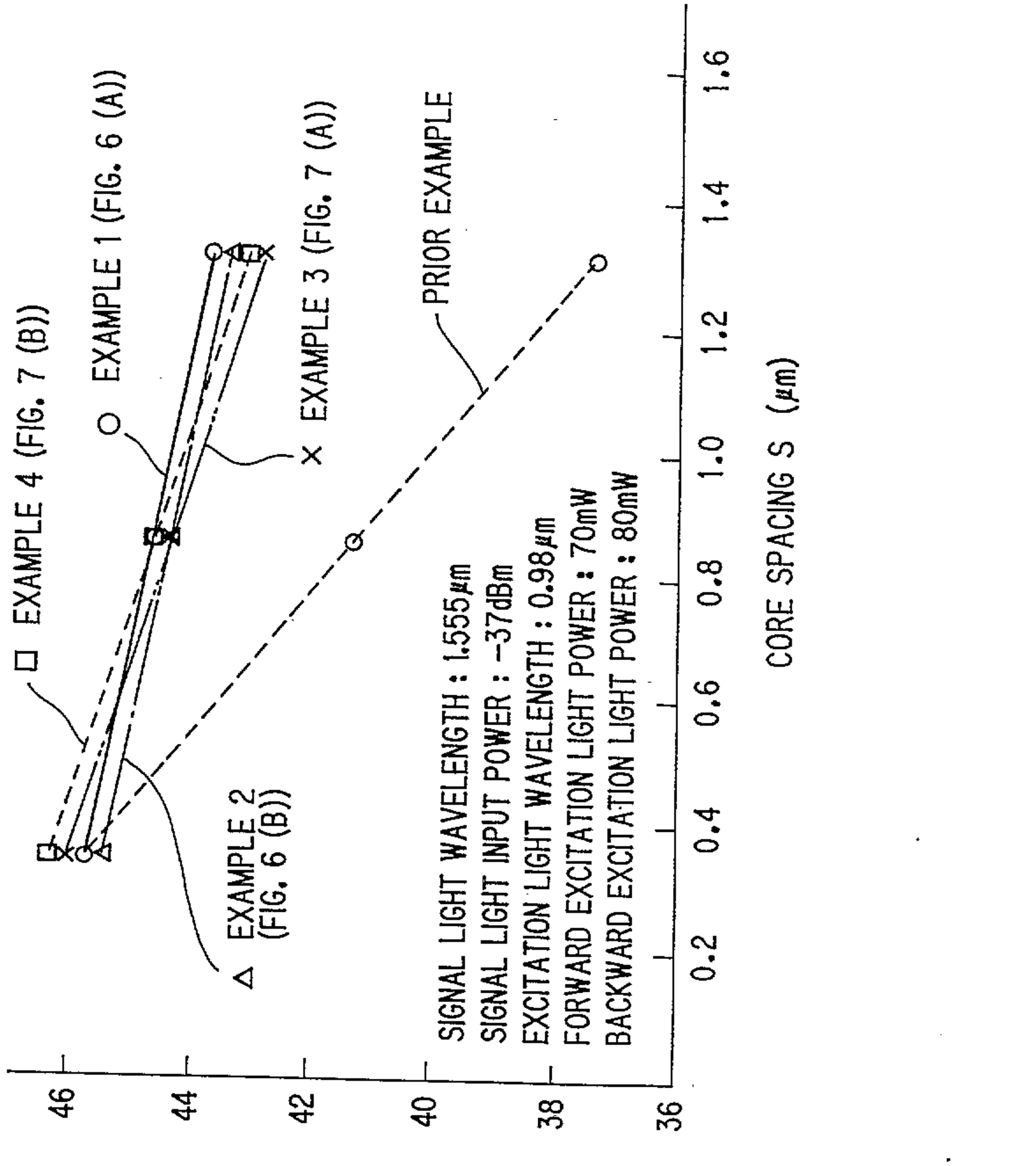

○ EXAMPLE 1 (FIG. 6 (A))
× EXAMPLE 3 (FIG. 7 (A))
PRIOR EXAMPLE
□ EXAMPLE 4 (FIG. 7 (B))
△ EXAMPLE 2 (FIG. 6 (B))
SIGNAL LIGHT WAVELENGTH : 1.555μm
SIGNAL LIGHT INPUT POWER : −37dBm
EXCITATION LIGHT WAVELENGTH : 0.98μm
FORWARD EXCITATION LIGHT POWER : 70mW
BACKWARD EXCITATION LIGHT POWER : 80mW
GAIN G (dB)
CORE SPACING S (μm)
46
44
42
40
38
36
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

FIG.5

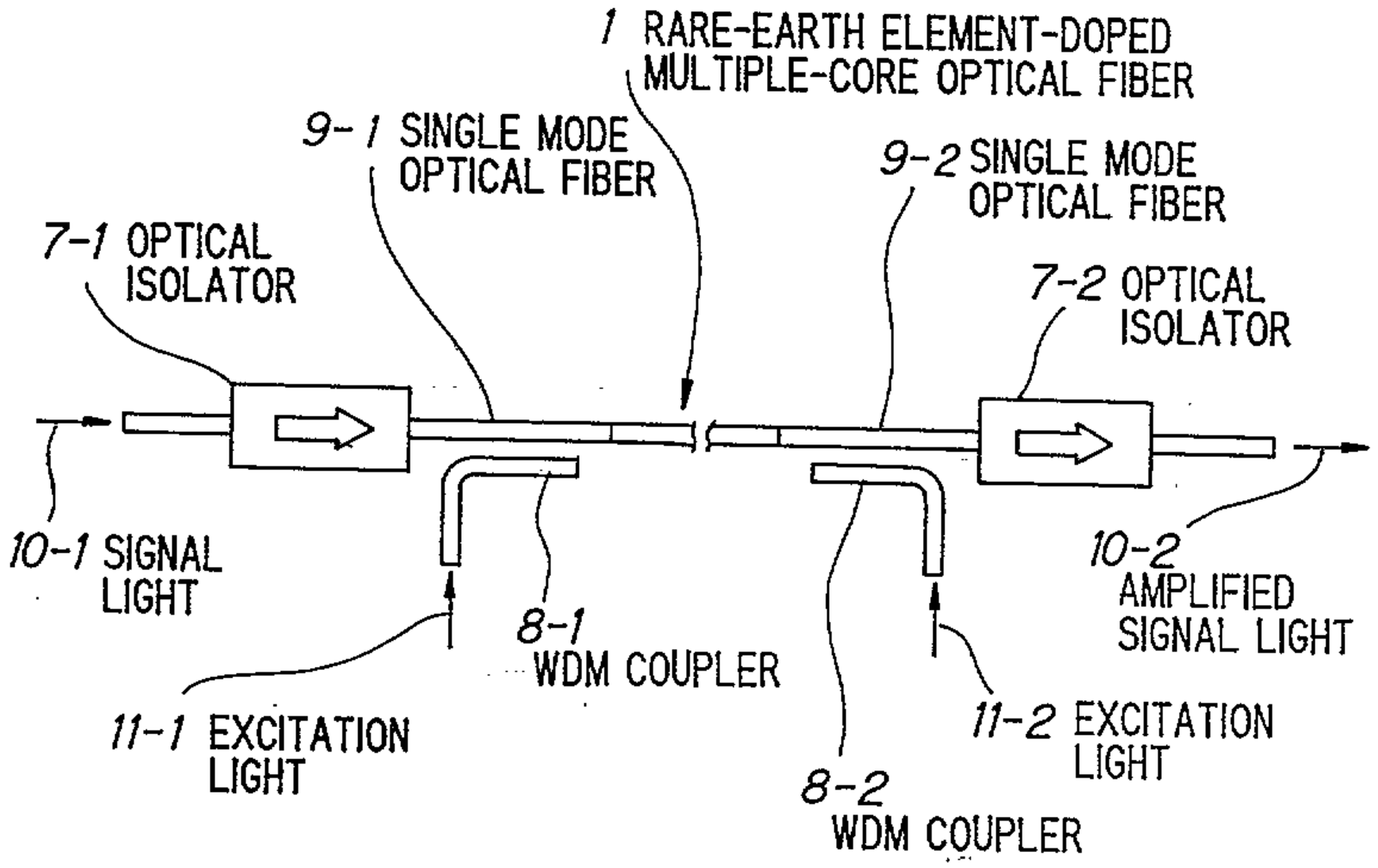

1 RARE-EARTH ELEMENT-DOPED MULTIPLE-CORE OPTICAL FIBER
9-1 SINGLE MODE OPTICAL FIBER
9-2 SINGLE MODE OPTICAL FIBER
7-1 OPTICAL ISOLATOR
7-2 OPTICAL ISOLATOR
10-1 SIGNAL LIGHT
10-2 AMPLIFIED SIGNAL LIGHT
8-1 WDM COUPLER
11-1 EXCITATION LIGHT
11-2 EXCITATION LIGHT
8-2 WDM COUPLER

FIG.6

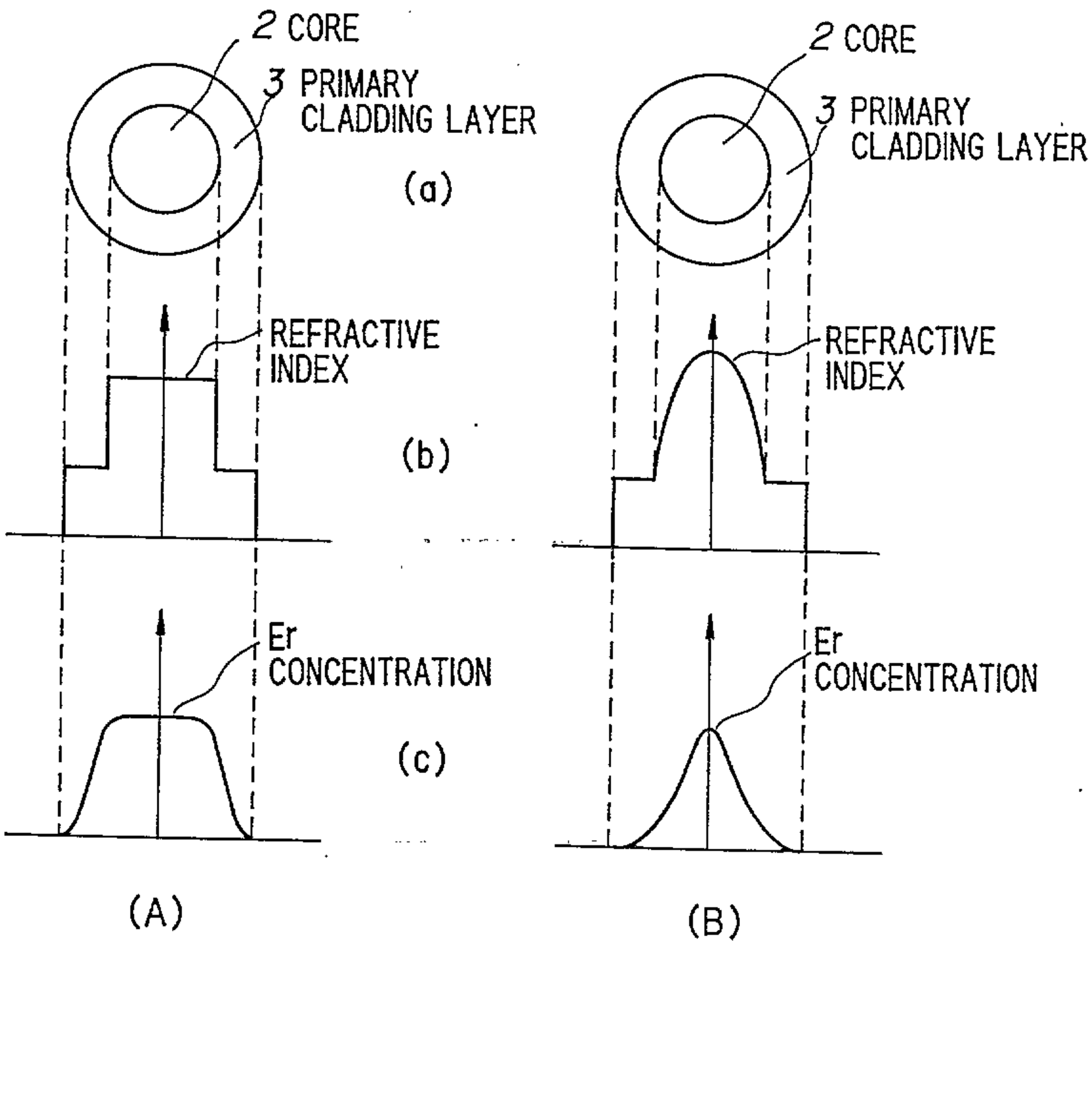

2 CORE
3 PRIMARY CLADDING LAYER
(a)
REFRACTIVE INDEX
(b)
Er CONCENTRATION
(c)
(A)
2 CORE
3 PRIMARY CLADDING LAYER
REFRACTIVE INDEX
Er CONCENTRATION
(B)

FIG. 7

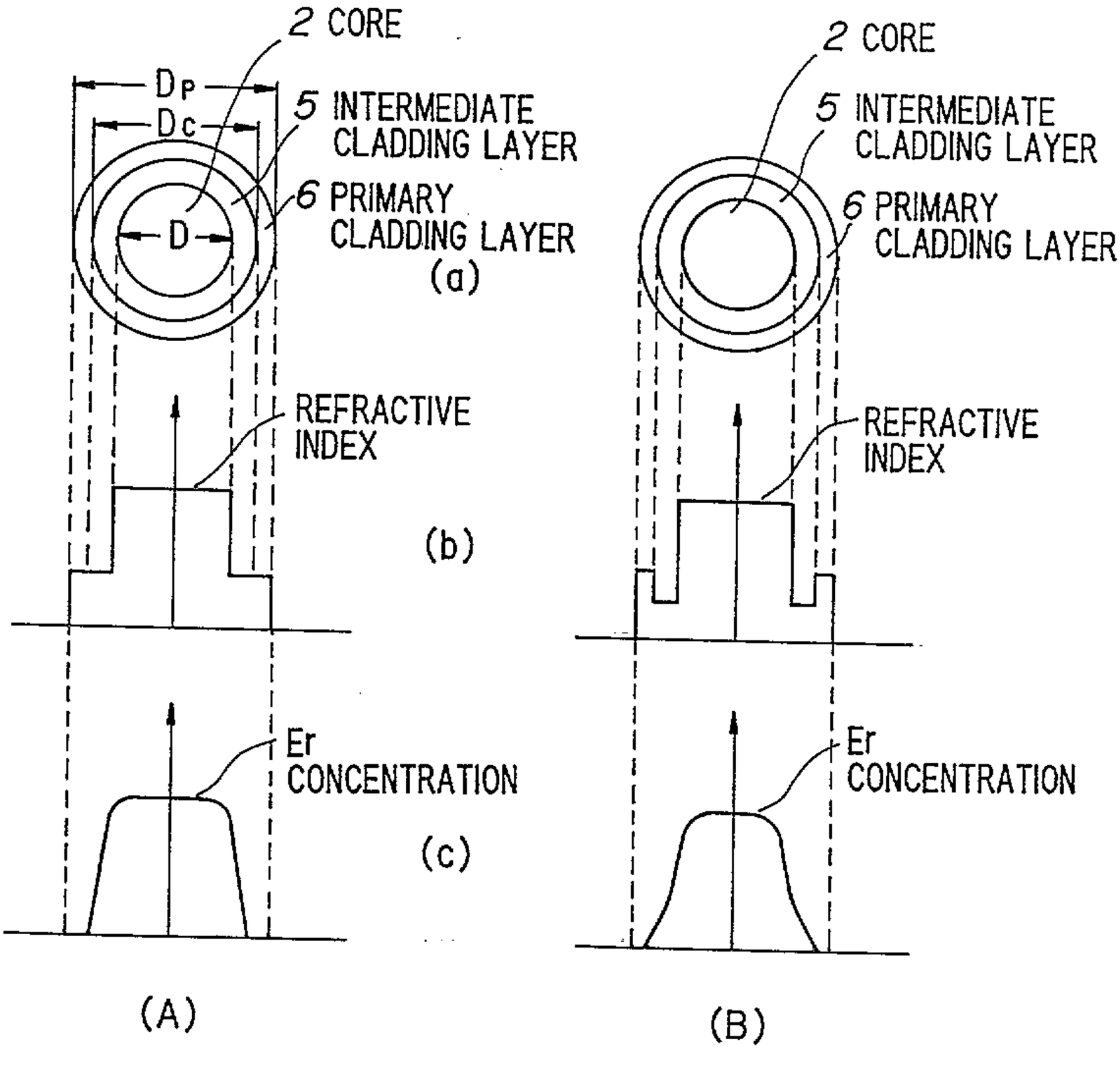

2 CORE
Dp
Dc
D
5 INTERMEDIATE CLADDING LAYER
6 PRIMARY CLADDING LAYER
(a)
REFRACTIVE INDEX
(b)
Er CONCENTRATION
(c)
(A)
2 CORE
5 INTERMEDIATE CLADDING LAYER
6 PRIMARY CLADDING LAYER
REFRACTIVE INDEX
Er CONCENTRATION
(B)

FIG. 8

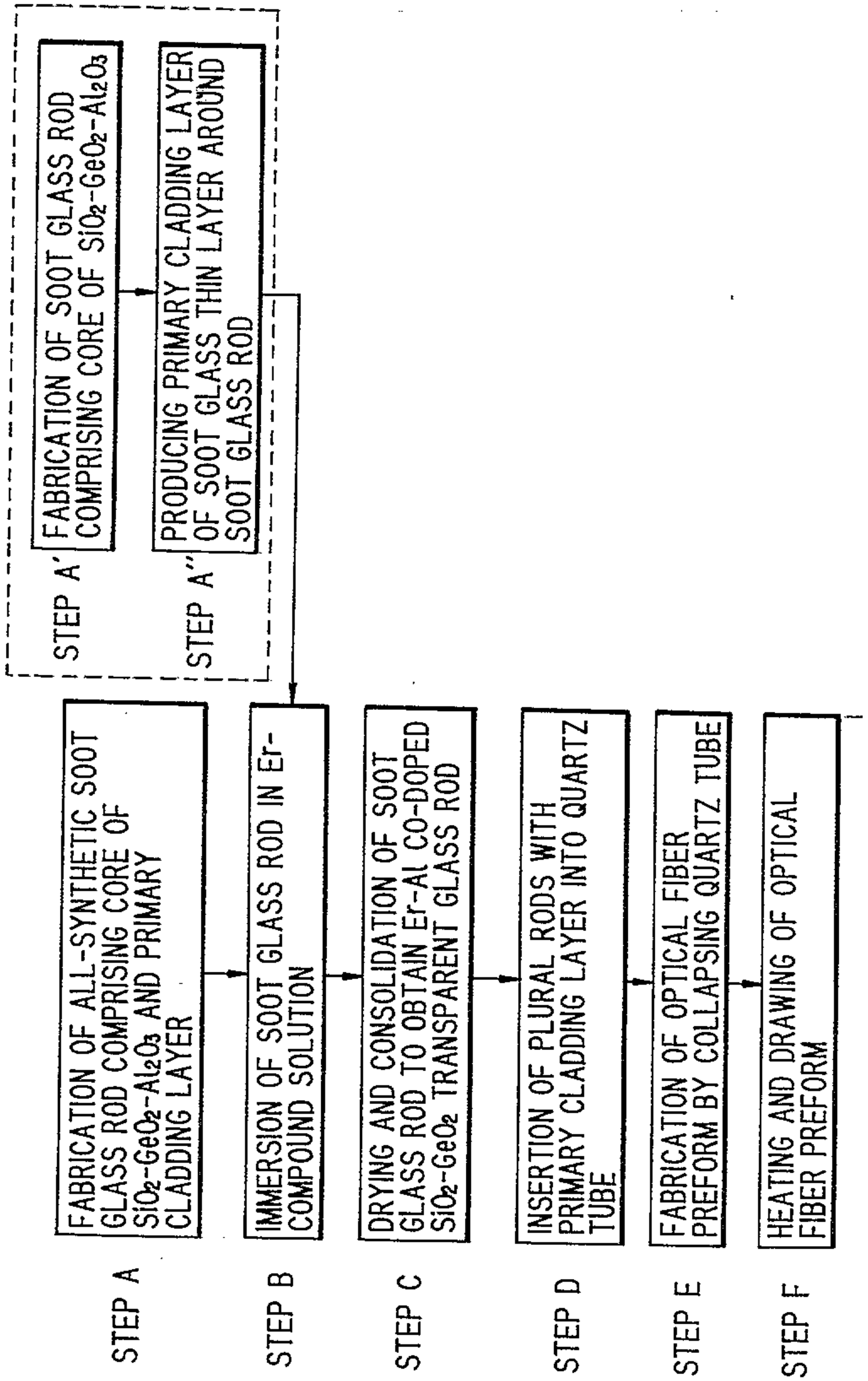

STEP A
FABRICATION OF ALL-SYNTHETIC SOOT GLASS ROD COMPRISING CORE OF SiO_2-GeO_2-Al_2O_3 AND PRIMARY CLADDING LAYER
STEP B
IMMERSION OF SOOT GLASS ROD IN Er-COMPOUND SOLUTION
STEP C
DRYING AND CONSOLIDATION OF SOOT GLASS ROD TO OBTAIN Er-Al CO-DOPED SiO_2-GeO_2 TRANSPARENT GLASS ROD
STEP D
INSERTION OF PLURAL RODS WITH PRIMARY CLADDING LAYER INTO QUARTZ TUBE
STEP E
FABRICATION OF OPTICAL FIBER PREFORM BY COLLAPSING QUARTZ TUBE
STEP F
HEATING AND DRAWING OF OPTICAL FIBER PREFORM
STEP A'
FABRICATION OF SOOT GLASS ROD COMPRISING CORE OF SiO_2-GeO_2-Al_2O_3
STEP A''
PRODUCING PRIMARY CLADDING LAYER OF SOOT GLASS THIN LAYER AROUND SOOT GLASS ROD

FIG. 9

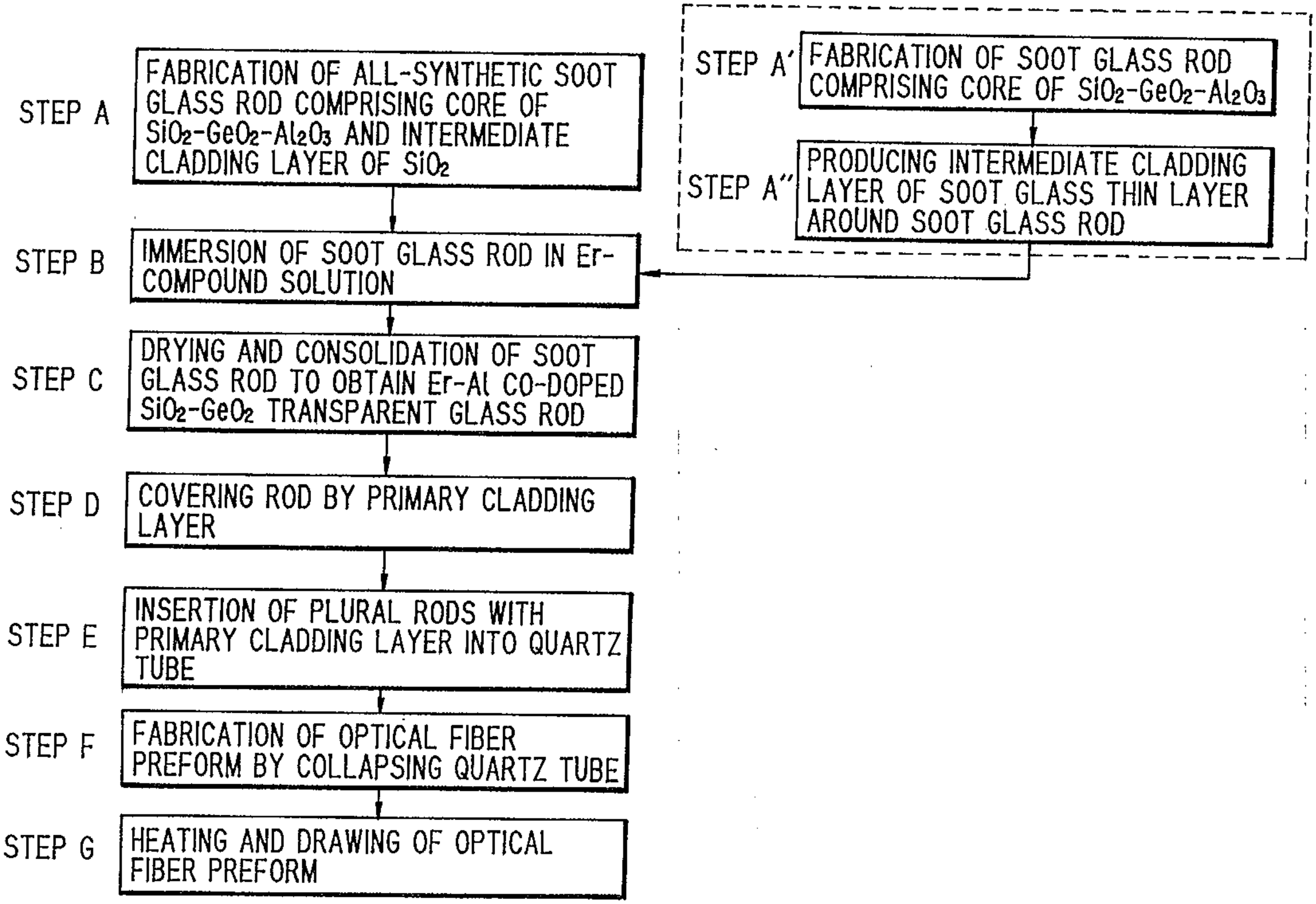
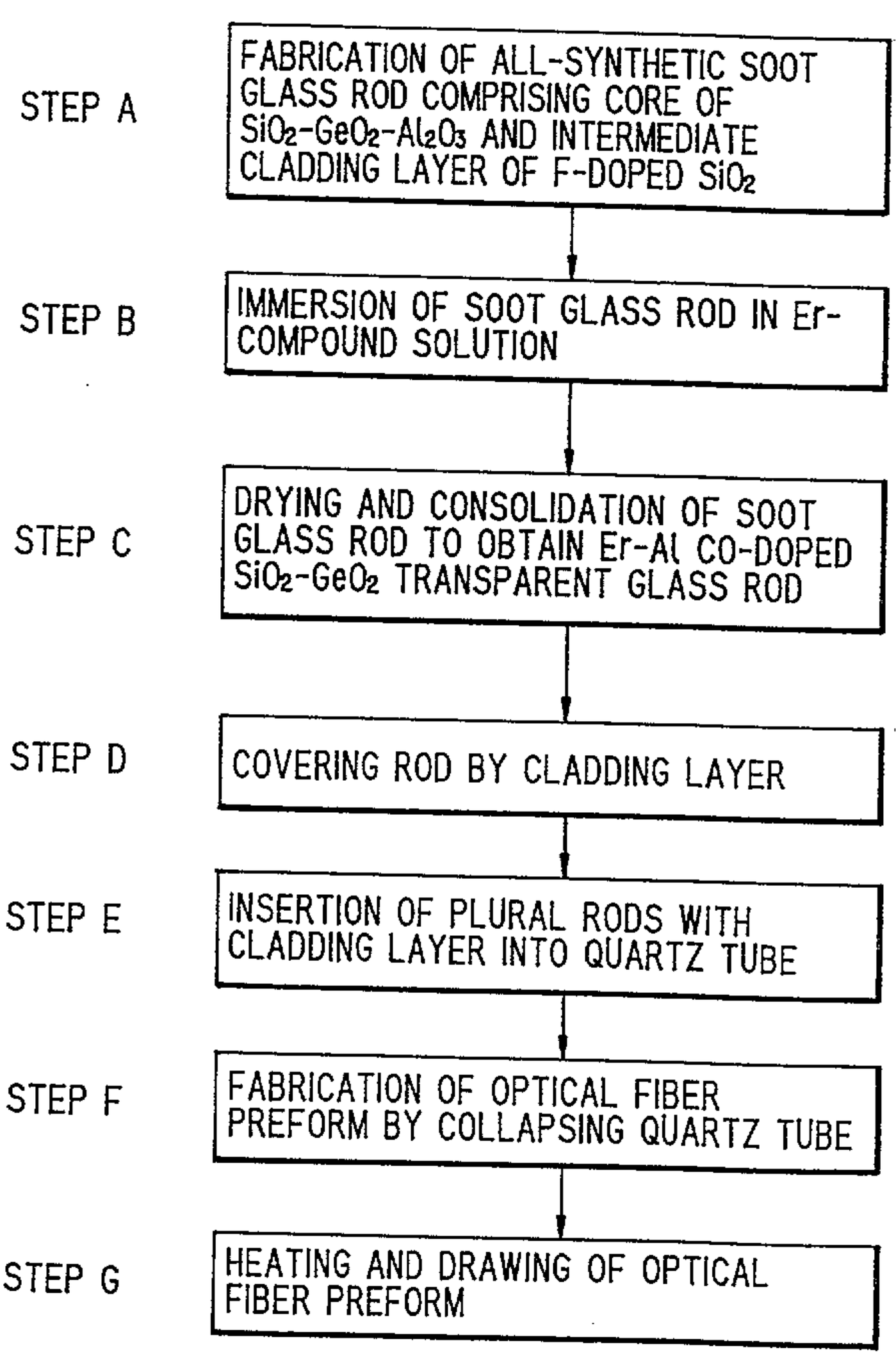
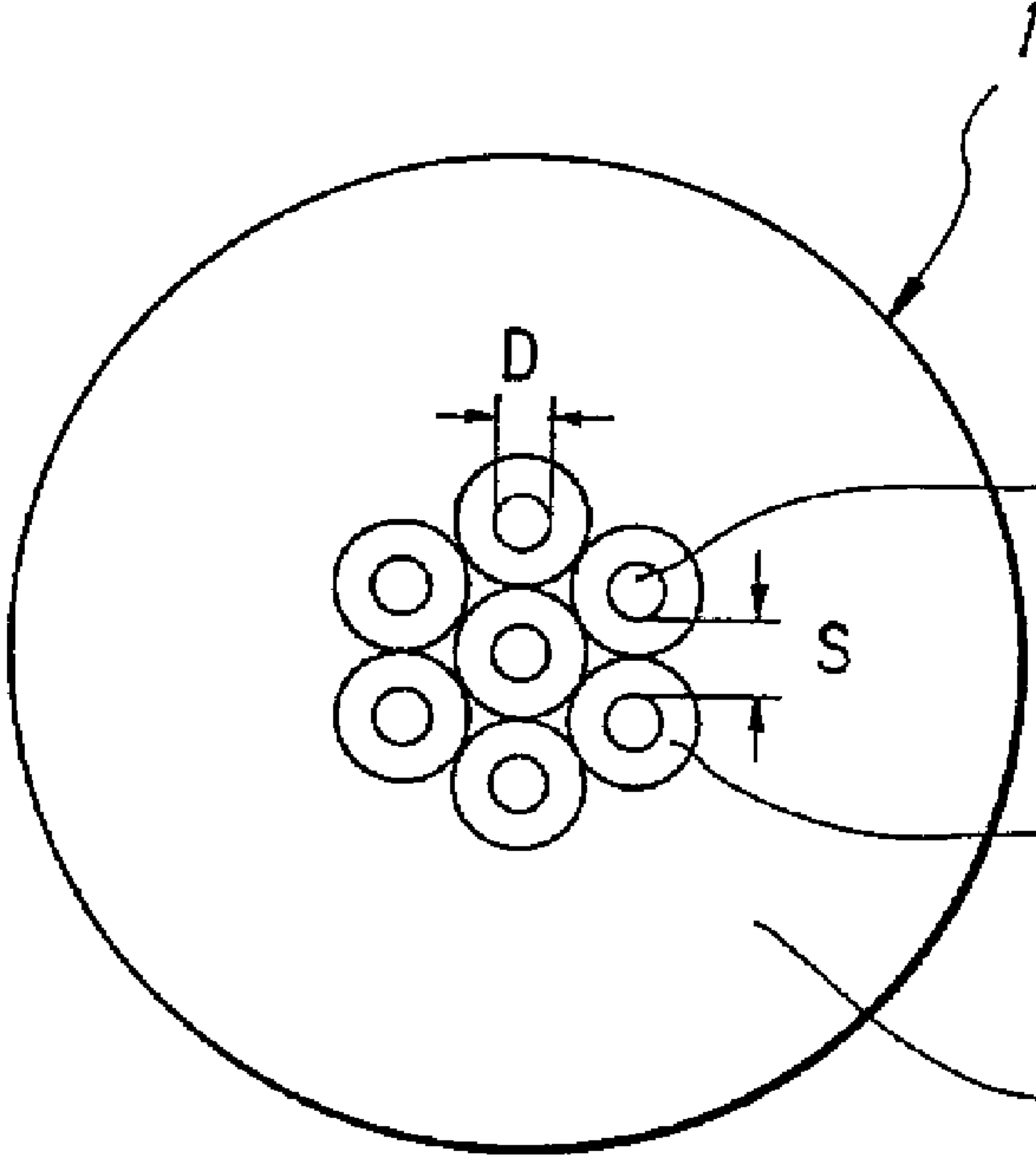


FIG. 10


STEP A
FABRICATION OF ALL-SYNTHETIC SOOT GLASS ROD COMPRISING CORE OF SiO_2-GeO_2-Al_2O_3 AND INTERMEDIATE CLADDING LAYER OF F-DOPED SiO_2
STEP B
IMMERSION OF SOOT GLASS ROD IN Er-COMPOUND SOLUTION
STEP C
DRYING AND CONSOLIDATION OF SOOT GLASS ROD TO OBTAIN Er-Al CO-DOPED SiO_2-GeO_2 TRANSPARENT GLASS ROD
STEP D
COVERING ROD BY CLADDING LAYER
STEP E
INSERTION OF PLURAL RODS WITH CLADDING LAYER INTO QUARTZ TUBE
STEP F
FABRICATION OF OPTICAL FIBER PREFORM BY COLLAPSING QUARTZ TUBE
STEP G
HEATING AND DRAWING OF OPTICAL FIBER PREFORM


1 RARE EARTH ELEMENT-DOPED MULTIPLE-CORE OPTICAL FIBER
D
2 CORE
S
3 PRIMARY CLADDING LAYER
4 OUTER CLADDING LAYER