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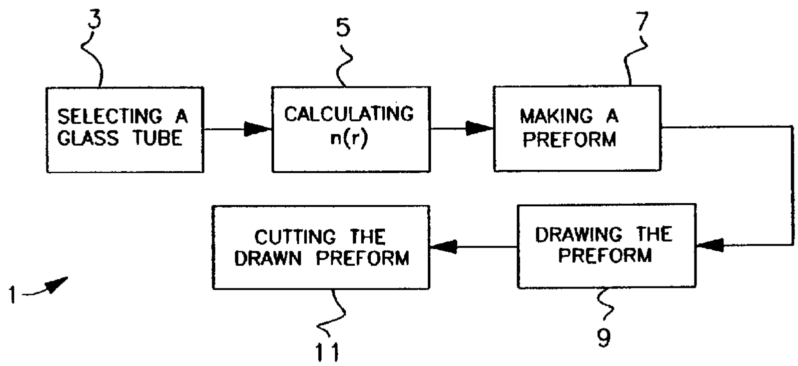
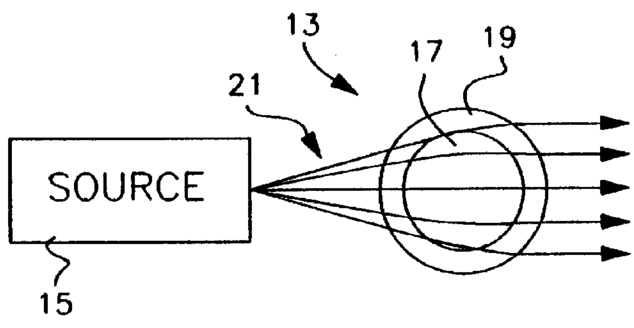
(54) **LENTILLE DE LUNEBERG A OUVERTURE PARTIELLE DOTEE D'UN NOYAU A GRADIENT D'INDICE ET D'UN BLINDAGE HOMOGENE, METHODE DE FABRICATION DE CETTE LENTILLE ET DIODE LASER A GRANDE OUVERTURE NUMERIQUE**

(54) **NONFULL APERTURE LUNEBERG-TYPE LENS WITH A GRADED INDEX CORE AND A HOMOGENOUS CLADDING, METHOD FOR FORMING THEREOF, AND HIGH NUMERICAL APERTURE LASER DIODE ASSEMBLY**





(57) Disclosed is a nonfull aperture Luneburg-type lens for correction of an adjacent light source. The lens includes a core having a circular cross-section and a graded refractive index, and a cladding enclosing the core. The cladding has a circular cross-section and a homogenous refractive index. Also disclosed is a method for forming the nonfull aperture Luneburg-type lens with a graded index core and a homogenous cladding, and a high numerical aperture laser diode assembly including the nonfull aperture Luneburg-type lens.

ABSTRACT

Disclosed is a nonfull aperture Luneburg-type lens for correction of an adjacent light source. The lens includes a core having a circular cross-section and a graded refractive index, and a cladding enclosing the core. The cladding has a circular cross-section and a homogenous refractive index. Also disclosed is a method for forming the nonfull aperture Luneburg-type lens with a graded index core and a homogenous cladding, and a high numerical aperture laser diode assembly including the nonfull aperture Luneburg-type lens.

WHAT IS CLAIMED IS:

1. A method for forming a nonful aperture Luneburg lens with a graded index core and a homogeneous cladding for correcting an adjacent light source, the lens having a normalized external radius, a core radius a, an object distance s_1 and an image distance s_2, the method comprising the steps of:

a) selecting the cladding, the cladding having a refractive index N, an internal radius and an external radius;

b) calculating a refractive index profile n(r), where r is the distance from the center of the core, the refractive index profile being calculated using the equation:

$$n = \frac{P_a}{a}\exp\{\Omega(\rho, s_1, P_a) + \Omega(\rho, s_2, P_a) - 2\Omega(\rho, 1, P_a) + 2\Omega(\rho, P_1, P_a)\}$$

wherein:

$P = P(r) = N * r, \text{ where } a \le r \le 1;$

$\rho = \rho(r) = n(r) * r, \text{ where } 0 \le r \le a;$

$P_a = N * a;$

$P_1 = N;$

$$\Omega(\rho, s_1, P_a) = \frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin\left(\frac{x}{s_1}\right)}{\sqrt{(x^2 - \rho^2)}}dx;$$

$$\Omega(\rho, P_1, P_a) = \frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin\left(\frac{x}{P_1}\right)}{\sqrt{(x^2 - \rho^2)}}dx;$$

$$\Omega(\rho, s_2, P_a) = \frac{1}{\pi} \int_{\rho}^{P_a} \frac{\arcsin\left(\frac{x}{s_2}\right)}{\sqrt{(x^2 - \rho^2)}} dx;$$

$$\Omega(\rho, 1, P_a) = \frac{1}{\pi} \int_{\rho}^{P_a} \frac{\arcsin(x)}{\sqrt{(x^2 - \rho^2)}} dx;$$

c) making a preform by introducing an optical material inside of said cladding selected in step (a) for obtaining the refractive index profile calculated in said step (b) and by collapsing said cladding and said introduced optical material; and

d) after said step (c), drawing the preform into a nonfull aperture Luneburg lens having a normalized external radius.

2. The method of claim 1, wherein in step (c), the optical material is introduced inside of said cladding by means of a modified chemical vapour deposition process.

3. The method of claim 1, further comprising a step (e) wherein after step (d), the drawn preform is cut to a predetermined length.

4. A nonfull aperture Luneburg lens for optical correction of an adjacent light source, the Luneburg lens having a normalized external radius, an object distance s_1, an image distance s_2 and being made from a drawn glass preform, the Luneburg lens comprising:

- a core having a circular cross section and a graded refractive index distribution, the core having a core radius a;

- a cladding enclosing the core, the cladding having a circular cross section, a homogeneous refractive index N, an internal radius and an external radius; and
- the core having a refractive index profile n(r), where r is the distance from the center of the core, the refractive index profile being calculated using the equation:

$$n = \frac{P_a}{a}\exp\{\Omega(\rho,s_1,P_a)+\Omega(\rho,s_2,P_a)-2\Omega(\rho,1,P_a)+2\Omega(\rho,P_1,P_a)\}$$

wherein:

$P = P(r) = N * r,\ where\ a \le r \le 1;$

$\rho = \rho(r) = n(r) * r,\ where\ 0 \le r \le a;$

$P_a = N * a;$

$P_1 = N;$

$$\Omega(\rho,s_1,P_a) = \frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin\left(\frac{x}{s_1}\right)}{\sqrt{(x^2-\rho^2)}}dx;$$

$$\Omega(\rho,P_1,P_a) = \frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin\left(\frac{x}{P_1}\right)}{\sqrt{(x^2-\rho^2)}}dx;$$

$$\Omega(\rho,s_2,P_a) = \frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin\left(\frac{x}{s_2}\right)}{\sqrt{(x^2-\rho^2)}}dx;\ \text{and}$$

$$\Omega(\rho,1,P_a) = \frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin(x)}{\sqrt{(x^2-\rho^2)}}dx.$$

5. A Luneburg lens according to claim 4, wherein the Luneburg lens has a cylindrical shape.

6. A Luneburg lens according to claim 5, wherein the glass preform has an outer portion made of fused silica.

7. A Luneburg lens according to claim 6, wherein the light source is a laser diode.

NONFULL APERTURE LUNEBERG-TYPE LENS WITH A GRADED INDEX CORE AND A HOMOGENOUS CLADDING, METHOD FOR FORMING THEREOF, AND HIGH NUMERICAL APERTURE LASER DIODE ASSEMBLY

FIELD OF THE INVENTION

The present invention relates to a method for forming a nonfull aperture Luneburg-type lens with a graded index core and a homogenous cladding, to a nonfull aperture Luneburg-type lens with a graded index core and a homogenous cladding, and to a high numerical aperture laser diode assembly.

BACKGROUND OF THE INVENTION

It is well known that laser diodes alone produce a beam that is divergent and astigmatic. To get better performances from a laser diode, lenses can be placed in front of the beam emitted by the laser diode, to improve its performances.

Different types of lenses can be used to correct the divergence, symmetry and astigmatism of laser diodes. Because laser diodes have an elongated rectangular aperture through which the beam is emitted, the most widely used type of lenses are the cylindrical lenses.

Existing cylindrical lenses used for correcting laser diodes are made of a homogenous medium, and have a cross-section either circular or noncircular. The cylindrical lenses of circular cross-section are easy to form, but they have poor optical performance when used at high numerical aperture, due to the large spherical aberrations. The cylindrical lenses of noncircular cross-section are capable of producing a better quality beam, but they are more difficult to produce since they require precision grinding of a relatively complex surface and precise centering of the two surfaces forming the lens. In use, the noncircular cylindrical lenses require precise positioning of the lens relative to the laser diode to obtain good results.

There are differenct types of lenses that have been termed as Luneburg lenses. The common threads for all of them are: the spherical symmetry (ball shape) or at least circular cross-section, the aberration-free imaging, except for chromatic aberration and field curvature, and the design principles where the graded index profile is calculated from pre-selected image and object positions. The main problem associated with the design of the Luneburg-type graded index lenses is to find the design whose refractive index distribution can be realized with the selected technology. With Luneburg-type cylindrical lens it is possible to preserve the circular cross section of the lens without introducing aberrations.

Known in the art are US Patent Nos. 5,080,706 and 5,155,631 (Snyder et al) which describe methods for fabrication of cylindrical microlenses of selected shape. These methods consist in first shaping a glass preform into a desired shape. Then, the preform is heated to the minimum drawing temperature and a fiber is drawn from it. The cross-sectional shape of the fiber is cut into sections of desired lengths. Finally, the fiber is cut into sections of desired lengths.

Also known in the art, is US Patent No. 5,181,224 (Snyder) which describes microlenses. This patent provides several microlens configurations for various types of optical corrections.

Another patent known in the art is US Patent No. 5,081,639 (Snyder et al), which describes a laser diode assembly including a cylindrical lens. This assembly comprises a laser diode and a cylindrical microlens whose cross-section is different from circular.

OBJECTS OF THE INVENTION

It is therefore an object of the present invention to provide a method of forming a nonfull aperture Luneburg-type lens with graded index core and homogenous cladding that is simple and that does not need precise grinding and precise centering. It is also another object of the present invention to provide a nonfull aperture Luneburg-type lens with graded index core and homogenous cladding that requires less stringent positioning relative to an adjacent source while offering good beam correction. It is also another object of the present invention to provide a high numerical aperture laser diode assembly that is simple to build, not expensive and that offers good performances.

SUMMARY OF THE INVENTION

According to the present invention, there is provided a method for forming a nonful aperture Luneburg lens with a graded index core and a homogeneous cladding for correcting an adjacent light source, the lens having a normalized external radius, a core radius a, an object distance s_1 and an image distance s_2, the method comprising the steps of:

a) selecting the cladding, the cladding having a refractive index N, an internal radius and an external radius;

b) calculating a refractive index profile n(r), where r is the distance from the center of the core, the refractive index profile being calculated using the equation:

$$n = \frac{P_a}{a} \exp\{ \Omega(\rho, s_1, P_a) + \Omega(\rho, s_2, P_a) - 2\Omega(\rho, 1, P_a) + 2\Omega(\rho, P_1, P_a) \}$$

wherein:

$P = P(r) = N * r,\ where\ a \le r \le 1;$

$\rho = \rho(r) = n(r) * r,\ where\ 0 \le r \le a;$

$P_a = N * a;$

$P_1 = N;$

$$\Omega(\rho, s_1, P_a) = \frac{1}{\pi} \int_{\rho}^{P_a} \frac{\arcsin\left(\frac{x}{s_1}\right)}{\sqrt{(x^2 - \rho^2)}} dx;$$

$$\Omega(\rho, P_1, P_a) = \frac{1}{\pi} \int_{\rho}^{P_a} \frac{\arcsin\left(\frac{x}{P_1}\right)}{\sqrt{(x^2 - \rho^2)}} dx;$$

$$\Omega(\rho, s_2, P_a) = \frac{1}{\pi} \int_{\rho}^{P_a} \frac{\arcsin\left(\frac{x}{s_2}\right)}{\sqrt{(x^2 - \rho^2)}} dx;$$

$$\Omega(\rho, 1, P_a) = \frac{1}{\pi} \int_{\rho}^{P_a} \frac{\arcsin(x)}{\sqrt{(x^2 - \rho^2)}} dx;$$

c) making a preform by introducing an optical material inside of said cladding selected in step (a) for obtaining the refractive index profile calculated in said step (b) and by collapsing said cladding and said introduced optical material; and

d) after said step (c), drawing the preform into a nonfull aperture Luneburg lens having a normalized external radius.

It is another object of the invention to provide a nonfull aperture Luneburg-type lens for optical correction of an adjacent light source, the Luneburg-type lens having a normalized external radius, an object distance s_1, an image distance s_2 and being made from a drawn glass preform, the Luneburg lens comprising:

- a core having a circular cross section and a graded refractive index distribution, the core having a core radius a;
- a cladding enclosing the core, the cladding having a circular cross section, a homogeneous refractive index N, an internal radius and an external radius; and
- the core having a refractive index profile n(r), where r is the distance from the center of the core, the refractive index profile being calculated using the equation:

$$n = \frac{P_a}{a}\exp\{\Omega(\rho,s_1,P_a)+\Omega(\rho,s_2,P_a)-2\Omega(\rho,1,P_a)+2\Omega(\rho,P_1,P_a)\}$$

wherein:

$$P = P(r) = N * r,\ where\ a \le r \le 1;$$

$$\rho = \rho(r) = n(r) * r,\ where\ 0 \le r \le a;$$

$$P_a = N * a;$$

$$P_1 = N;$$

$$\Omega(\rho,s_1,P_a) = \frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin\left(\frac{x}{s_1}\right)}{\sqrt{(x^2-\rho^2)}}dx;$$

$$\Omega(\rho,P_1,P_a)=\frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin\left(\frac{x}{P_1}\right)}{\sqrt{(x^2-\rho^2)}}dx;$$

$$\Omega(\rho,s_2,P_a)=\frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin\left(\frac{x}{s_2}\right)}{\sqrt{(x^2-\rho^2)}}dx;$$

$$\Omega(\rho,1,P_a)=\frac{1}{\pi}\int_{\rho}^{P_a}\frac{\arcsin(x)}{\sqrt{(x^2-\rho^2)}}dx.$$

Preferably, the nonfull aperture Luneburg-type lens has a cylindrical shape and is drawn from a drawn glass preform.

Also, another object of the present invention is to provide a high numerical aperture laser diode assembly comprising:

a laser diode source having an elongated rectangular aperture for emitting a laser beam through the elongated rectangular aperture;

a Luneburg-type cylindrical lens parallel to the elongated rectangular aperture and set in front of the laser beam for optical correction thereof, the Luneburg-type lens comprising:

- a core having a circular cross-section and a graded refractive index distribution; and
- a cladding enclosing the core, the cladding having a circular cross-section and a homogenous refractive index.

Preferably, the Luneburg-type lens is drawn from a glass preform.

A non restrictive description of a preferred embodiment will now be given with reference to the appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a method for forming a nonfull aperture Luneburg-type lens with a graded index core and a homogenous cladding according to the invention;

FIG. 2 is a perspective view showing a nonfull aperture

Luneburg-type lens with a graded index core and a homogenous cladding according to the invention; and

FIG. 3 is a side elevational view of a high numerical aperture laser diode assembly according to the invention.

DESCRIPTION OF A PREFERRED EMBODIMENT

Several characteristics are used to describe a lens. More particularily, to describe lenses that are made from a glass preform, the characteristics are: the size of the core, which is described by its radius, the size of the cladding, described by its external radius, the object distance, and the image distance. To lighten this text, the radius of the core is called a, the external radius of the cladding is unitary (normalized), the object distance is called s_1 and the image distance is called s_2. These values are scalable to whatever the external size of the cladding is. Moreover, the expression "optically correcting" refers to aberration correction but does not include chromatic aberration and field curvature.

Referring now to Figure 1, there is shown a method 1 for forming a nonfull aperture Luneburg-type lens with a graded index core and a homogenous cladding. The first step of the method consists in selecting 3 a glass tube 19, which will be used as a cladding, characterized by its external and internal radii and by a refractive index N.

The next step of the method consists in calculating 5 a refractive index profile n(r), where r is the distance from the center of the core. That refractive index profile takes into account the desired characteristics of the lens to be made. These characterisitics are the desired core radius, the desired object distance and the desired image distance for a unit cladding radius. The refractive index profile is calculated with formula (1).

$$n=\frac{P_a}{a}\exp\{\Omega(\rho,s_1,P_a)+\Omega(\rho,s_2,P_a)-2\Omega(\rho,1,P_a)+2\Omega(\rho,P_1,P_a)\} \quad (1)$$

In this formula, the expression ρ relates to the refractive index of the core of the lens, such as described in equation (2):

$$\rho = \rho(r) = n(r)*r, \text{ where } 0 \le r \le a; \quad (2)$$

This refractive index of the core ρ is calculated with equation (3).

$$\ln\left(\frac{a}{r}\right) = \frac{2}{\pi}\int_{\rho}^{P_a}\frac{(f(k) - F(k))}{(k^2 - \rho^2)^{\frac{1}{2}}}dk, \qquad 0\le\rho\le P_a \quad (3)$$

where:

$$f(k) = \frac{1}{2}(\arcsin\frac{k}{s_1} + \arcsin\frac{k}{s_2} + 2*\arccos(\mathbf{k}) \quad (4)$$

and

$$F(k) = \int_{a}^{1}\frac{k\,dr}{r(P^2(r) - k^2)^{\frac{1}{2}}} \qquad 0\le k\le P_a \quad (5)$$

In equations (1), (2) and (4), P_a and P_1 are determined by:

$$P_a = N*a; \quad (6)$$

$$P_1 = N; \quad (7)$$

where P_a and P_1 are particular cases of P(r) which is a specially selected function for the cladding, such as defined in the next equation:

$$P = P(r) = \mathbf{N^*r},\ where\ a \le r \le 1; \qquad (8)$$

The expression $\Omega(\rho,s,P)$ of equation (1) can be generally expressed by the following equation:

$$\Omega = \frac{1}{\pi}\int_{\rho}^{P_a} \frac{\arcsin(\frac{x}{s})}{\sqrt{(x^2 - \rho^2)}}\, dx \qquad (9)$$

Yet, for the Ω expressions used in equation (1), they represent the following equations:

$$\Omega(\rho, s_1, P_a) = \frac{1}{\pi}\int_{\rho}^{P_a} \frac{\arcsin(\frac{x}{s_1})}{\sqrt{(x^2-\rho^2)}}\, dx; \qquad (10)$$

$$\Omega(\rho, s_2, P_a) = \frac{1}{\pi}\int_{\rho}^{P_a} \frac{\arcsin(\frac{x}{s_2})}{\sqrt{(x^2-\rho^2)}}\, dx; \qquad (11)$$

$$\Omega(\rho, 1, P_a) = \frac{1}{\pi}\int_{\rho}^{P_a} \frac{\arcsin(x)}{\sqrt{(x^2-\rho^2)}}\, dx; \qquad (12)$$

$$\Omega(\rho, P_1, P_a) = \frac{1}{\pi}\int_{\rho}^{P_a} \frac{\arcsin(\frac{x}{P_1})}{\sqrt{(x^2-\rho^2)}}\, dx. \qquad (13)$$

The following step consists in making a preform by introducing 7 graded optical material inside of the chosen glass tube and by collapsing the glass tube and the introduced graded optical material into the preform, to obtain the refractive index profile calculated in the previous step.

The graded optical material may be deposited directly inside the tube by means of a modified chemical vapour deposition process.

Another way to make a preform consists of using an ion-exchange process. That process is used to modify the refractive index profile of a glass rod to correspond to the refractive index profile calculated in step (b), and to introduce the glass rod inside of the glass tube of step (a), the glass rod becoming the core of the preform and the glass tube the cladding of the preform.

Step (c) may also further consist of verifying whether the refractive index profile of said preform is substantially equal to the refractive index profile calculated in step (b), and if necessary, repeating steps (a), (b) and (c) and slightly changing deposition parameters until the refractive index profile of the preform is substantially equal to the refractive index profile calculated in step (b).

Finally, the last step consists of drawing 9 the preform into a Luneburg-type lens having desired radius. The method 1 may also comprise one last step which consists of cutting 11 the drawn preform to a predetermined length.

This method is thus simple and it does not need precise grinding nor precise centering. The circular shape of the lens makes it easily scalable for wide range of focal lengths.

Referring now to Figures 2 and 3, there is shown a nonfull aperture Luneburg-type lens 13 for optical correction of an adjacent light source 15, such as a laser diode. That lens 13 has a cylindrical shape. It has a core 17 of circular cross-section and graded refractive index distribution. The lens 13 has a cladding 19 enclosing the core 17. The cladding 19 has a circular cross-section and a homogenous refractive index. The refractive index distribution inside the core 17 corrects the aberrations of the cladding 19 but only for the light rays that also pass through the core 17, hence the name nonfull aperture lens. That lens 13 could be made, for example, from a drawn glass preform having an outer portion made of fused silica.

The lens has to be placed in front of the aperture (not shown) of the light source 15 to optically correct its beam. Its circular form and very good aberration correction at high numerical apertures makes this lens 13 less sensitive to positioning errors.

Referring now to Figure 3, there is shown a high numerical aperture laser diode assembly. This assembly comprises a laser diode source 15 and a nonfull aperture Luneburg-type cylindrical lens 13. The laser diode source 15 has an elongated rectangular aperture (not shown) for emitting a laser beam 21 through that aperture. The Luneburg-type cylindrical lens 13 is placed parallel to the elongated rectangular aperture and set in front of the laser beam 21 for optically correcting that beam.

The Luneburg-type lens 13 has a core 17 and a cladding 19. The core 17 has a circular cross-section and a graded refractive index distribution, and the cladding 19 encloses the core 17. The cladding 19 has a circular cross-section and a homogenous refractive index. The Luneburg-type lens 13 may be made from a drawn glass preform having a cladding made of fused silica.

Although a preferred embodiment of the invention has been described in detail herein and illustrated in the accompanying drawings, it is to be understood that the invention is not limited to this precise embodiment and that various changes and modifications may be effected therein without departing from the scope or spirit of the invention.

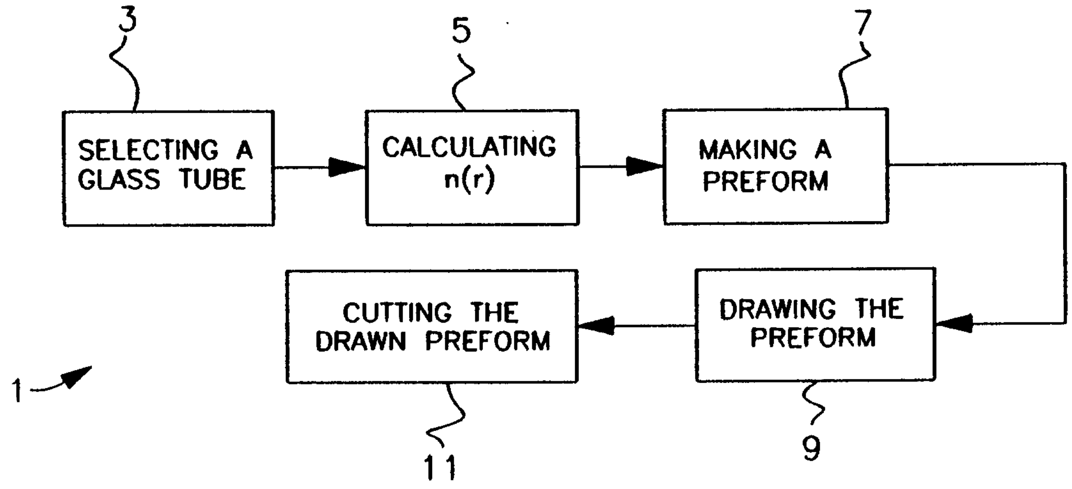


FIG. 1

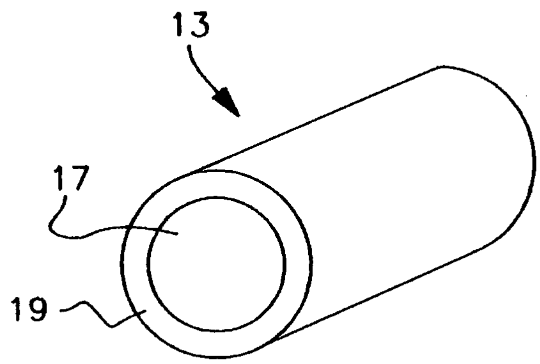


FIG. 2

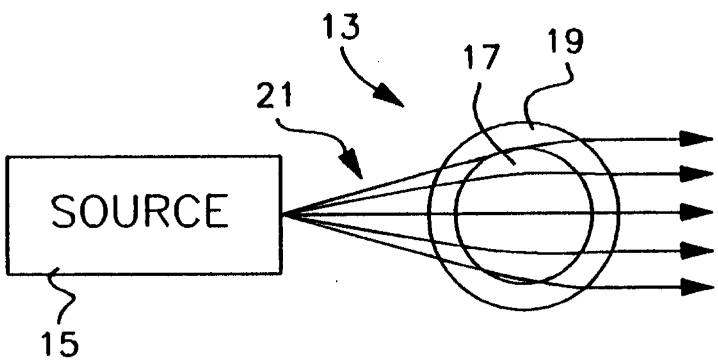
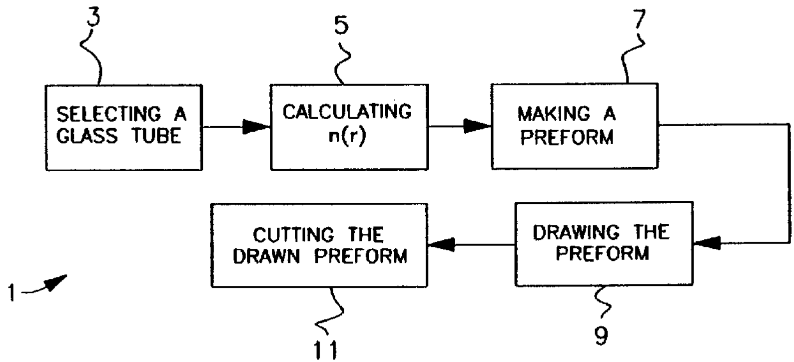


FIG. 3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SELECTING A GLASS TUBE
CALCULATING n(r)
MAKING A PREFORM
CUTTING THE DRAWN PREFORM
DRAWING THE PREFORM
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11
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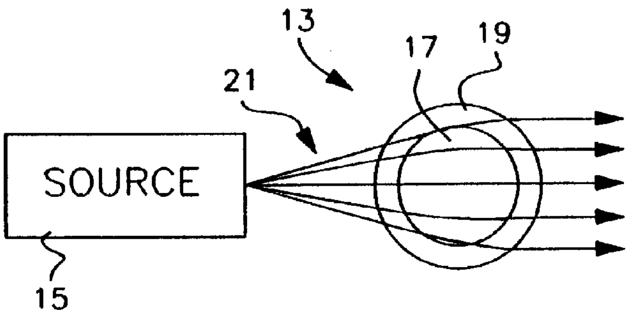
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