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CA 2313357 C 2006/11/07

(11)(21) 2 313 357

(12) BREVET CANADIEN
CANADIAN PATENT

(13) C

(22) **Date de dépôt/Filing Date**: 2000/07/04
(41) **Mise à la disp. pub./Open to Public Insp.**: 2001/01/05
(45) **Date de délivrance/Issue Date**: 2006/11/07
(30) **Priorité/Priority**: 1999/07/05 (CA2,276,939)

(51) **Cl.Int./Int.Cl.** *G02B 7/02* (2006.01), *G02B 6/26* (2006.01), *G02B 6/42* (2006.01), *H01S 5/40* (2006.01), *G02B 6/36* (2006.01), *H01S 5/00* (2006.01)
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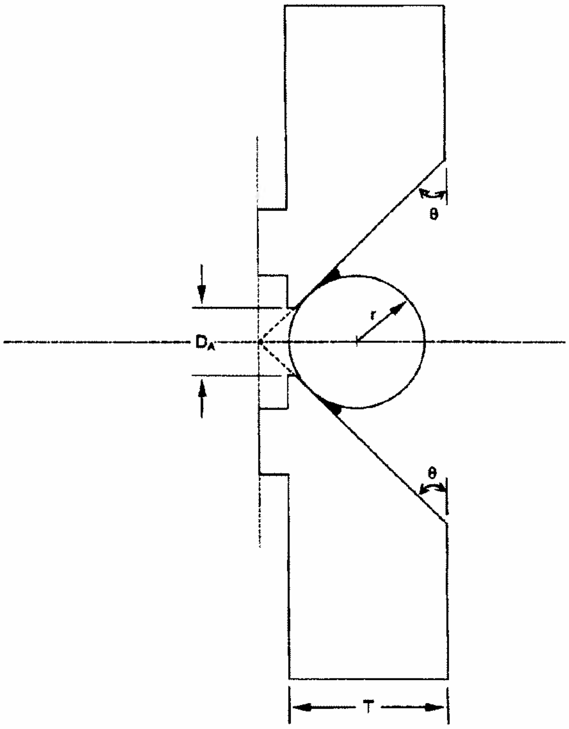
(54) Titre : PORTE-MINI-LENTILLE AUTOFOCUS
(54) Title: AUTO-FOCUS MICROLENS HOLDER



(57) **Abrégé/Abstract**:

A microlens holder for supporting at least one microlens in alignment with a light source is described. Each of the microlenses has a radius and a back focal length varying linearly with the radius. The microlens holder includes a base having at least one V-groove therein for receiving the at least one microlens, each of the V-grooves having a pair of side walls, both side walls being tilted by an angle θ relative to the plane of the emitting light source. The value is defined by the relationship $\cos(\theta) = (1 + k)^{-1}$, where k is a positive constant factor associated with the at least one microlens. The microlens holder allows auto-focussing of the light source, independently of the exact diameter of the microlenses mounted in the holder. The optical alignment of the microlenses is made easier as well.

Abstract

A microlens holder for supporting at least one microlens in alignment with a light source is described. Each of the microlenses has a radius and a back focal length varying linearly with the radius. The microlens holder includes a base having at least one V-groove therein for receiving the at least one microlens, each of the V-grooves having a pair of side walls, both side walls being tilted by an angle θ relative to the plane of the emitting light source. The value is defined by the relationship $\cos(\theta) = (1+k)^{-1}$, where k is a positive constant factor associated with the at least one microlens. The microlens holder allows auto-focussing of the light source, independently of the exact diameter of the microlenses mounted in the holder. The optical alignment of the microlenses is made easier as well.

AUTO-FOCUS MICROLENS HOLDER

Field of the invention

The present invention relates to an auto-focus microlens holder, particularly useful for collimation or conditioning of the light beams radiated by laser diodes or laser diode arrays.

Description of the prior art

The outstanding features of high-power semiconductor laser diodes as compared to conventional, bulky laser sources give them a bright future for use in applications like optical pumping of solid-state lasers, light illuminator systems, range finders, and direct coupling into optical fibres for convenient delivery of laser light up to remote targets, as desired in various industrial and medical applications. High-power semiconductor laser devices are mostly available in the form of elongated, thin laser diode bars comprising a plurality of individual laser emitters set along an axis parallel to the semiconductor PN junction plane of the emitters. A schematic drawing of a laser diode bar is shown in FIG. 1.

Common laser diode bars typically comprise 10 to 50 individual equally spaced emitters, which spread over a total width generally set to the 1-cm standard width. Each individual emitter has typical dimensions of 50-200 µm × 1 µm, and they are represented by the small filled rectangles in FIG. 1. The laser cavity length, defined as the spacing between both front and rear cleaved facets, is on the order of 500-1000 µm. Laser diode bars made from the AlGaAs material system for emission of laser light in the 790-860 nm wavelength range can routinely emit tens of Watts of CW optical power. When even higher optical output powers are required from the laser source, several laser diode bars of the same geometry can be stacked one above the other using suitable mounting means to give a two-dimensional laser diode array. The mounting means is designed to hold the laser bars firmly in place while ensuring proper electrical biasing and ______________________________ cooling of each bar. The resulting total output power scales directly with the number of stacked laser diode bars.

According to the well-known diffraction theory of coherent laser light, the beams radiated out from the individual emitters of a laser bar spread (diverge) from the normal propagation direction perpendicular to the plane of the laser front facet. The rate of divergence of the beams along any given direction depends critically upon the size of the individual emitters along the same direction. As seen in FIG. 1, the divergence angles of the beam escaping from a laser emitter of the size as given above are typically 40° FWHM (full width at half maximum) along the direction perpendicular to the junction plane, and 10° FWHM along the direction parallel to the junction plane. Unfortunately, the highly divergent character of the beams, particularly along the direction perpendicular to the junction plane, makes laser diode bars or arrays unsuited for most high-power applications unless proper optical elements are employed for reducing the divergence of the beams. It is then said that the beams need to be properly collimated. To ensure efficient collection of the emitted laser light, the collimation optics must present a high numerical aperture, and such optics are said to be fast. This explains why the direction perpendicular to the junction plane is usually denoted as the fast axis. Accordingly, the direction parallel to the junction plane is commonly referred to as the slow axis.

A “collective” collimation of the entire set of laser beams escaping from the plurality of identical laser emitters disposed linearly along the slow axis of a laser diode bar can be performed in a quite efficient manner along the most critical axis (fast axis) by using a single optical element shaped as an elongated glass rod. The glass rod is set in front of the laser diode bar in such a way that its longitudinal axis is parallel to the slow axis of the laser bar. The elongated rod acts as a cylindrical microlens that collimates along the fast axis the beams radiated by all emitters. Proper alignment of the cylindrical microlens is obtained by placing it so that its longitudinal axis, passing through the centre of the microlens, is made coincident with the plane formed by the optical axes of the individual emitters of the laser diode bar. The beams radiated from the plurality of laser emitters impinge on the curved side of the microlens, and are then refracted through it while propagating perpendicularly to the longitudinal axis of the microlens. Finally, to ensure efficient collimation of the transmitted laser beams, that is, minimising their residual divergences after collimation, the front facet of the laser diode bar must lie within the back focal plane of the cylindrical microlens. In practice, several successful designs of cylindrical microlenses with high numerical apertures have been developed for collimation along the fast axis of the beams radiated by laser diode bars. These designs include for instance simple and low-cost cylindrical step-index fibre microlenses, cylindrical fibre microlenses with graded-index core (GRIN microlenses), and cylindrical microlenses with an aspheric shape. Collimation of laser diode bars using step-index ordinary optical fibres and microlenses with an aspheric shape is detailed in U.S. Patents nos. 4,785,459 (Baer) and 5,081,639 (Snyder *et al.*), respectively.

The principle of collimating laser beams along the fast axis of a laser diode bar by using properly positioned high numerical aperture microlenses can be readily extended to the collimation of laser diode arrays by stacking, with suitable support means, several identical cylindrical microlenses, each of them being individually registered to a laser diode bar of the array. Known in the art are U.S. Patents nos. 5,825,803 (Labranche *et al.*) and 5,875,058 (R. E. Grubman), which describe beam collimation or conditioning of laser diode array assemblies by means of GRIN microlenses. A schematic side view of a stacked laser diode array whose bars are collimated by cylindrical microlenses is depicted in FIG. 2. The collimated laser array assembly shown in this figure comprises three laser diode bars, and the figure is a side view of the assembly, so that the microlenses are seen only from their cross-section, which has a circular shape in this example. As it is readily seen, the longitudinal axis of each microlens is aligned with the optical axis of the laser diode bar that faces the microlens. Consequently, the spacing *P* (pitch) between the centres of the microlenses is equal to the spacing along the fast axis of the laser diode bars mounted in their support structure. The positioning and fine alignment of the microlenses relative to the laser diode array require the use of a dedicated support structure in which the microlenses are mounted and held in place using proper adhesives or fixing means. A technique now well known in the art for this purpose consists in inserting the cylindrical microlenses into grooves formed in a lens holder, thus resulting in an array of several correctly-spaced microlenses mounted parallel to each other and all lying in the same plane. After the microlenses have been mounted into the holder, the resulting microlens array then forms a firm, unitary assembly that can then be placed in front of the laser diode array with correct positioning and orientation so that each laser diode bar is collimated by its own cylindrical microlens. As shown in FIG. 2, the spacing *d* between the plane of the front facets of the laser diode bars and the cylindrical microlens array must be fine tuned until the front facets lie within the back focal plane of the microlenses (having ideally all the same focal length *f*) to ensure the lowest residual divergence for the collimated beams. After the microlens array has been correctly positioned, it is then attached to the laser diode array to form a collimated laser diode array assembly.

An example of a side view of a microlens holder placed in front of a three-bar laser diode array is depicted schematically in FIG. 3. Details about the design of such a microlens holder are disclosed in U.S. Patents nos. 5,526,373 and 5,668,825 (Karpinsky). This design consists in forming properly spaced parallel grooves of rectangular cross-section in base substrate material. The size of the grooves must be adapted to the diameter of the microlenses to ensure adequate alignment and firm attachment of the individual microlenses loaded into the grooves. In the example illustrated in FIG. 3, the three cylindrical microlenses have the same diameter, so they are preferably inserted into grooves having the same size. In practice, however, the cylindrical microlenses often present some variations in their diameters which can be caused, for instance, by the manufacturing tolerances of the fibre drawing process (typically ±2%), since microlenses are generally fabricated in the same way as optical fibres.

A tight control over the outer diameter of the microlenses must be exercised when they are intended to be loaded into microlens holders with grooves of rectangular shape, otherwise severe degradation of the collimation efficiency of the microlens array will result. Because the diameter of the fibres needs to be tightly controlled, the additional quality control steps that must be carried out are expensive.

Some of the drawbacks that could be encountered when using microlens holders with rectangularly shaped grooves are illustrated schematically in FIG. 4. Apart from the obvious problem of inserting microlenses with oversized cross-section into precisely sized grooves, it is readily seen that the correct centering of a microlens having too small a diameter relative to the size of the grooves is nearly impossible. Due to the very short focal length of the microlenses used for collimation along the fast axis (on the order of a few hundreds microns), even a minute misalignment of the microlenses results in a collimated beam that will propagate off-axis with a sizeable tilt angle, resulting in an increased overall beam divergence. In addition, since the whole microlens holder must be precisely spaced from the front facet of the laser diode bars, a microlens of incorrect diameter and mounted into a rectangular groove will not be properly spaced from its corresponding laser diode bar, thus degrading further the collimation of the beam. This problem comes from the fact that the focal length of most types of microlenses depends on the diameter of the microlenses.

An example of microlens holder with V-shaped grooves whose symmetrical side walls are tilted at an angle of 90° with respect to each other is taught in U.S. Patent no. 5,828,683 (B.L. Freitas). Unfortunately, V-shaped grooves tilted at 90° do not allow the front facets of the laser diode bars to remain in the back focal plane of the cylindrical microlens independently of the diameter of the microlens.

Summary of the invention

An object of the present invention is to provide a microlens holder comprising V-shaped grooves in which graded-index or step-index fibre microlenses with circular cross-section are loaded in order to keep the front facets of laser diode bars in the focal plane of the microlenses, independently of the exact diameter of the microlenses loaded into the grooves.

In accordance with a first aspect of the invention, there is therefore provided a microlens holder for supporting at least one microlens of circular cross-section in alignment with a light source, each of the at least one microlens having a radius and a back focal length varying linearly with said radius according to a gradient defining a positive constant factor k, the microlens holder comprising:

a base having at least one V-groove therein for receiving the at least one microlens, each of said at least one V-groove having a pair of side walls, both side walls being tilted by an angle θ relative to the plane of the emitting light source, said value of θ being defined by:

$$\theta = \cos^{-1}\left(\frac{1}{1+k}\right).$$

In accordance with another aspect of the invention, there is also provided a microlens assembly comprising:

a microlens holder as described above;

at least one microlens mounted into said at least one V-groove of the microlens holder; and

bonding means for bonding said at least one microlens to said V-groove.

In accordance with another aspect of the invention, there is also provided a microlens holder for supporting at least one ball microlens in alignment with a light source having an optical axis, each of the at least one ball microlens having a radius and a back focal length varying linearly with said radius according to a gradient defining a positive constant factor k, the microlens holder comprising:

a base having at least one recess therein for receiving the at least one microlens, each of said at least one recess having a conical side wall symmetrical around the optical axis and tilted by an angle θ relative to the plane of the emitting light source, said value of θ being defined by:

$$\theta = \cos^{-1}\left(\frac{1}{1+k}\right).$$

Preferably, the microlens assembly as described above may be used in combination with a laser diode array for conditioning light emitted along either the slow or fast axes of the laser diode array. Alternatively, two microlens assemblies as described above may be used with the microlenses of one holder perpendicular to the microlenses of the other holder, in combination with a laser diode array for conditioning light along both its slow and fast axes.

Brief description of the drawings

The present invention and its advantages will be more easily understood after reading the following non-restrictive description of preferred embodiments thereof, made with reference to the following drawings in which:

FIG. 1 (Prior Art) is a schematic perspective view of a laser diode bar showing the typical divergence angles along both fast and slow axes of the beam radiated by the plurality of emitters of the bar.

FIG. 2 (Prior Art) is a schematic side view illustrating cylindrical microlenses for collimation along the fast axis of the beams emitted by a stacked laser diode array comprising three laser diode bars.

FIG. 3 (Prior Art) is a schematic side view of a collimated three-bar stacked laser diode array showing the microlens holder with grooves of rectangular shape adapted to the size of the microlenses.

FIG. 4 (Prior Art) illustrates some problems encountered when using cylindrical microlenses of varying diameters with a microlens holder formed with grooves of rectangular shape.

FIG. 5 is a schematic diagram illustrating the basic principle of the present invention.

FIG. 6 is a schematic side view of a collimated stacked laser diode array wherein collimation of the laser diode bars is achieved by cylindrical microlenses of different diameters loaded into an holder with V-shaped grooves having side walls with suitable tilt angle.

FIG. 7A shows a top view of a microlens holder in accordance with a preferred embodiment of the invention.

FIG. 7B shows a front view of a microlens holder in accordance with the same preferred embodiment of the invention.

FIG. 7C shows a side view of a microlens holder in accordance with the same preferred embodiment of the invention.

FIG. 8 depicts a side view of a holder for spherical ball lenses in accordance with another embodiment of the invention.

Description of a preferred embodiment of the invention

As mentioned previously, one object of the present invention is to provide a microlens holder for cylindrical microlenses with circular cross-section in which correct spacing of the microlenses relative to the front facet of the laser diode bar to collimate is obtained independently of the exact diameter of the microlenses. This appealing "auto-focus" property is made possible by forming into a microlens holder grooves with a V-shaped cross-section, in which the microlenses are loaded therein.

The auto-focus property can be exploited using V-shaped grooves with side walls tilted at special angles, and this is another object of the present invention to provide means for determining this angle, which depends on the specific design of the selected microlenses, but not on their diameter. Since this specially determined tilt angle allows for mounting microlenses of varying diameter in a same microlens holder, it is a further object of the present invention to provide a means for relaxing the manufacturing dimensional tolerances on the diameter of fibre microlenses intended for collimation of laser diode bars or arrays.

It is another object of the present invention to provide a means to make easier and much faster the optical alignment of the cylindrical microlenses loaded in the grooves formed in a holder, by taking advantage of the self-centering property of microlenses with circular cross-section loaded into properly-positioned V-shaped grooves. This self-centering property is independent of the diameter of the microlenses.

The optical coupling systems developed for coupling light between optical fibres as well as for coupling light from single-emitter laser diodes into optical fibre ends may benefit from the present invention. These optical coupling systems often make use of small lenses having a perfectly spherical shape with a typical diameter on the order of a few mm's. These lenses are generally known as ball lenses. Mounting spherical ball lenses into a lens holder having a V-shaped receptacle with side walls tilted at angles as prescribed by the invention would allow correct placement of the exit aperture of a light emitting device in the back focal plane of the ball lens, regardless of the exact lens diameter. It is therefore another object of the present invention to provide a holder for ball lenses of spherical shape for which the exact placement of either the light emitter to collimate or the focus plane for light to be focused is independent of the diameter of the ball lens mounted into the holder.

Although the principle of the present invention applies primarily to the collimation of laser diode bars (both in the form of single devices or mounted in two-dimensional stacked arrays), lens holders designed according to the present invention could be of widespread use. For instance, the positioning of arrays of microlenses used for focusing the incoming light onto the photosensitive pixel elements of array imagers (CCD image sensors, IR thermal imagers, arrays of micro-bolometers or pyroelectric elements, etc...) may benefit from the use of microlens holders comprising V-shaped grooves designed following the principles of the invention. Likewise, the principle can be found useful for collimation or conditioning of the light escaping from non-laser sources such as light-emitting diodes or optical fibre outputs wherein correct spacing between the collimating lens and the output aperture of the light emitting device is critical.

The present invention will be described by first outlining its basic principles with reference to the schematic drawing presented in FIG. 5. In the preferred embodiment of the invention, an elongated fibre microlens having a circular cross-section is seated into a V-shaped groove formed in a holder made of a suitable material. A laser diode bar is positioned in such a way that its cleaved front facet from which the laser beam is radiated coincides with the trough of the V-shaped groove. In FIG. 5, the laser beam propagates upward and its outer edges are outlined by the solid arrows.

The optical axis of the laser beam is perpendicular to the front facet of the laser diode bar and this optical axis passes through the centre of the microlens. The thickness T of the microlens holder, given by the spacing between the plane of the front facet of the laser diode bar and the crests of the groove, is not critical to the operation of the invention. However, the microlens holder must be thick enough to allow the microlens of radius *r* (half-diameter) to be properly seated into the groove. The plane of the front facet of the laser diode bar is separated from the vertex of the microlens by the working distance *d*, as illustrated in FIG. 5. The vertex is the point lying on the contour of the microlens which intersects the optical axis and which is nearest to the laser diode bar. The plane of the front facet of the laser diode bar must coincide with the back focal plane of the microlens in order to provide the best collimation of the beam radiated by the laser diode bar. Stated otherwise, the working distance *d* must be set equal to the back focal length (*bfl*) of the microlens. The back focal length of any given microlens depends on the microlens' radius as well as on the specific spatial refractive index distribution of the material from which the microlens is made. The V-shaped groove comprises two symmetrical side walls tilted by the same angle θ relative to the plane of the front facet of the laser diode bar.

One major aspect of the invention is to show that there exists a value of the tilt angle θ of the side walls that will make the working distance *d* equal to the back focal length of the microlens. Referring to FIG. 5, simple trigonometric formulas readily show that the angle θ is related to the radius *r* of the microlens by:

$$\cos(\theta) = \frac{r}{r+d} \quad . \tag{1}$$

The working distance *d* must be equal to the back focal length *bfl* of the microlens, so that the above equation can then be rearranged in the following manner:

$$\cos(\theta) = \frac{1}{1+\frac{bfl\,(r)}{r}} \tag{2}$$

where the dependency of the back focal length upon the radius of the microlens have been emphasised. Tilting the side walls at the angle θ as given by Eq. (2) ensures therefore that the vertex of the microlens will be correctly spaced from the front facet of the laser diode bar. Moreover, it can be seen that the angle θ of the side walls which form the V-shaped groove does not depend on the radius of the microlens, provided that the microlens design is such that the back focal length varies linearly with the microlens' radius, that is, *bfl*(*r*) = *kr*, where *k* is a positive constant factor depending on the specific design of the microlens. The knowledge of the constant factor *k* therefore permits calculation of the angle θ according to the following formula:

$$\theta = \cos^{-1}\left(\frac{1}{1+k}\right) \qquad 0° \le \theta \le 90° \quad . \tag{3}$$

Although the principle of the invention requires the use of cylindrical microlenses whose back focal length varies linearly with the lens' radius, it appears that this limitation is not a severe drawback because two of the most appealing types of microlens for collimation of the fast axis of laser diode bars fall within this category.

The first type is quite simple and low cost since it consists in elongated rods (for instance step-index fibres with the jacket removed) in which the refractive index is homogeneous everywhere inside the microlens. As it is well known in the art, the back focal length of these step-index fibre microlenses is given by:

$$bfl_{STEP-INDEX} = \frac{r\,(2-n)}{2\,(n-1)} \tag{4}$$

where n is the refractive index at the working wavelength of the glass material from which the microlenses are made. As a rule of thumb, one gets bfl(r) = 0.5r for step-index microlenses made of fused silica (n ≈ 1.5). The above equation also reveals that step-index microlenses can be used for collimation of laser diode bars provided that their refractive index n is smaller than 2. Otherwise, the focal plane of the microlens would be positioned inside the lens. It should be noted that the back focal length of spherical ball lenses is calculated from Eq. (4) as well.

The second microlens design that falls within the category discussed above is characterised by a gradual and smooth reduction of the refractive-index profile from the centre of the microlens up to the outer limits of the core. These graded-index (GRIN) microlenses are preferably of the non-full aperture Luneberg type with a homogeneous cladding, which shows high collimation efficiency along with low spherical aberration on the transmitted laser beam, even at high numerical aperture. The design and fabrication of these GRIN microlenses are detailed in U.S. Patent nos. 5,607,492 and 5,638,214 (Doric). The back focal length of this type of GRIN microlens commercially available from Doric Lenses Inc. (Ancienne-Lorette, Québec, Canada) exhibits a linear dependency with the microlens' radius since:

$$bfl_{GRIN} = 0.37\,r \tag{5}$$

As compared to a step-index microlens of the same radius, a GRIN microlens generally has a shorter back focal length. This makes these microlenses very attractive for efficient gathering of the highly-diverging beams radiated by laser diode bars, since the front facet of the bar can be set closer to the vertex of the microlens. However, GRIN microlenses suitable for use in a microlens holder fabricated according to the principle of the present invention are not limited to non-full aperture Luneberg-type lenses and could be, for instance, full aperture Luneberg-type lenses with or without homogeneous cladding, or non-full aperture GRIN lenses with a profile different from the Luneberg type and with or without homogeneous cladding. In fact, it should be emphasised that any microlens ______________________________ design of circular cross-section and leading to a linear dependency of the back focal length upon the radius of the microlens (with a known constant factor) could be suitable for collimation of the laser light emitted by laser diode bars according to the present invention.

Typically, the angle θ at which the side walls of the V-shaped groove should be tilted is obtained simply by reporting the values of the constant factor k for both step-index and GRIN microlens types in Eq. (3), thus giving:

$$\theta_{STEP\ INDEX} = 48.2° \quad \text{(for fused-silica fibers with } n \approx 1.5\text{)}$$

$$\theta_{GRIN} = 43.1° \qquad (k = 0.37)$$

Positioning the front facet of a laser diode bar at the trough of a V-shaped groove with side walls tilted at angles as given above will then ensure proper placement of the front facet in the back focal plane of the microlens loaded into the groove, and this, regardless of the exact diameter of the microlenses, provided that the tilt angle of the side walls is suited to the microlens type.

As another example, spherical ball lenses are often made of a glass material with high refractive index to shorten their back focal length (thereby increasing their numerical aperture) without excessive curvature of the lenses. For instance, ball lenses made of a LaSF N9 *Schott* glass material having a refractive index around 1.83 for 830-nm light wavelength could be mounted in a holder with a V-shaped receptacle whose side walls are tilted at an angle given by

$$\theta_{BALL} = 24.9° \qquad \text{(for LaSF N9 ball lenses with } n = 1.83\text{)} .$$

The chief advantages offered by the present invention as compared to the prior art are best exemplified by referring to the schematic drawing of FIG. 6. The figure illustrates a stacked laser diode array whose individual laser beams are collimated by an array of microlenses mounted into a holder with V-shaped grooves designed according to the present invention. The stacked laser diode array assembly consists of four laser diode bars with identical characteristics and mounted in a suitable support structure not shown in the drawing. The laser diode bars are positioned in such a way that their individual front facets lie in the same plane, which is made coincident with the plane formed by the troughs of the V-shaped grooves as well. Microlenses of the same type but having possibly different diameters are inserted into the grooves. In this specific example, they serve for collimation of the laser beams along the fast axis of the laser diode bars. Even though the diameter of the various microlenses could vary significantly, the front facets of all laser diodes bars would remain in the back focal plane of the microlenses, therefore promoting efficient collimation of the laser beams transmitted through the microlenses.

The possibility of using microlenses with varying diameters in the same holder is particularly attractive for replacement of damaged microlenses by spare microlenses fabricated from another batch. In addition, those skilled in the art will recognise that the diameter of any given microlens to be loaded in a V-shaped groove designed in the way as described above needs not be exactly the same along the length of the microlens, provided that the diameter varies in a linear fashion along the length of the microlens.

Another significant advantage of the present invention relies on the automatic self-alignment feature offered by the V-shaped grooves. This advantage can be exploited by first ensuring adequate registration of the laser diode bars with the troughs of the V-shaped grooves, that is, the periodicity of the grooves must match the spacing between successive laser diode bars. Due to the special shape of the grooves, loading of a microlens with circular cross-section into any of the grooves will provide self-alignment of the longitudinal axis of the microlens with the optical axis of the laser diode bar registered to the groove. This self-alignment feature greatly facilitates the mounting of microlens arrays, and it leads to collimated output laser beams displaying minimum residual divergence since all individual collimated laser beams are directed along the same direction, parallel to the optical axes of the laser diode bars. Although the laser diode array depicted in FIG. 6 comprises four laser diode bars along with their corresponding microlenses, it should be readily apparent that the principles of the present invention could be implemented for collimation of laser diode arrays made up of any number of laser diode bars.

One preferred embodiment of a microlens holder fabricated following the principle of the present invention is depicted in the three views presented in FIGS.

7A through 7C. Referring first to the top view of FIG. 7A, it is shown that the microlens holder has preferably the shape of a rectangular mounting frame having a central part that is free of material. The microlens holder comprises two parallel support members having a top major surface in which V-shaped grooves have been formed with side walls tilted at angles prescribed by the selected microlens type. A plurality of elongated fibre microlenses of suitable length are loaded into the V-shaped grooves to form an array of microlenses with their individual longitudinal axes parallel to each other and aligned with the optical axes of the corresponding laser diode bars, the latter being not shown in FIG. 7. The number of microlenses is preferably equal to the number of bars forming the stacked laser diode array assembly, and the spacing between the troughs of the grooves is preferably equal to the spacing between the laser diode bars. An anti-reflection coating can be deposited on the microlenses to minimise optical reflection losses. In this preferred embodiment of the microlens holder, the microlenses are supported by the V-shaped grooves only over regions of limited length at both ends of the microlenses. The length of the V-shaped grooves is given by the width of the support members of the microlens holder. This design permits the front facets of the laser diode bars to be located in the back focal plane of the microlenses while avoiding direct contact of the front facets with any part of the microlens holder. The risks of accidental damages to the laser front facets are therefore minimised. As a result, adequate positioning of the laser front facets relative to the microlens holder requires that the clearance between the inner side surfaces of the support members is made slightly larger than the width of the laser diode bars (typically 1 cm). Attachment of the microlenses to the holder via grooves of reduced length and positioned at both ends of the microlenses is possible by recognising that the typical diameter (about 600 μm to 2-3 mm) of the microlenses used for collimation of laser diode arrays provides sufficient mechanical rigidity to the microlenses. As a consequence, mechanical deformation of the microlenses attached by their ends and having a length of typically 1-1.5 cm is not a problem in real practice.

FIG. 7B is a front view of the microlens holder showing the microlenses placed in the V-shaped grooves. The microlenses can be bonded to the side walls of the grooves by using proper adhesive well known in the art such as UV-curing epoxy cement or any other bonding technology compatible with the materials from which the microlenses and the holder are made. The microlens holder can be fabricated from materials like various ceramics, silicon, or various metals. It is preferable that the selected material be easily machinable to allow higher fabrication yields along with tight mechanical tolerances. According to the preferred embodiment of the invention, it can be seen that the material from which the microlens holder is made needs not be optically transparent to the beams radiated by the laser diode bar or array because the beams do not travel through any part of the microlens holder after escaping from the laser diode bars. Likewise, the adhesive used for bonding of the microlenses neither needs to be optically transparent nor needs to be index matched to the material of the microlenses. The V-shaped grooves formed on the top major surface of the support members can be machined with side walls tilted at suitable angle using a dicing saw with a properly shaped saw blade, by electric-discharge machining, or by laser machining.

As it is shown from the side view of FIG. 7C, both support members of the microlens holder have flat underside surfaces that permit attachment of the whole microlens holder to the mounting structure of the laser diode array. The undersides of the support members are set in contact with proper flat surfaces of the mounting structure of the laser diode array. The thickness of the support members is determined from the need to ensure that the plane of the front facets of the laser diode bars coincides with the back focal plane of the microlenses, after the microlens holder has been affixed to the laser diode array assembly.

The use of microlens holders fabricated according to the present invention is not limited to the collimation along the fast axis of laser diode arrays. Hence, collimation of laser diode arrays along the slow axis, orthogonal to the fast axis, can be performed using such a microlens holder as well. In this case, the spacing between the V-shaped grooves would correspond to the spacing between the individual laser emitters of the laser bars, while the length of the microlenses would be determined from the number of laser bars stacked in the array and from their pitch. As it is well known in the art, collimation along the slow axis of laser diode arrays using cylindrical microlens arrays requires that the laser diode bars be identical to each other and that the emitters of each laser diode bar be aligned relative to the corresponding emitters of the other stacked laser bars. The lower divergence of the laser diode beams along the slow axis promotes the use of cylindrical microlenses with lower numerical aperture and longer focal length as compared to their counterparts designed for collimation along the highly-diverging fast axis. As a result, the microlens array used for collimation along the slow axis is positioned farther from the plane of the front facet of the laser emitters. Although the various positioning and alignment tolerances are less demanding for efficient collimation along the slow axis, the present invention favours faster and easier alignment of the cylindrical microlenses and permits less stringent tolerances on the diameter of the cylindrical microlenses as well.

Although the microlens holder depicted in the views of FIG. 7A-7C allows mounting of a maximum of six microlenses, the number of microlenses to be used can be varied according to the specific requirements dictated by the characteristics of the laser diode array to be collimated. For instance, the microlens holder may comprise only one microlens loaded into a V-shaped groove for collimation of a single laser diode bar. In the same way, it will be obvious to those skilled in the art that various changes in the dimensions and structure of the embodiment of the microlens holder described above can be carried out without departing from the scope of the present invention.

As stated previously, the scope of the present invention can be extended to the mounting of spherical ball lenses. The side view of an embodiment of a holder for mounting spherical ball lenses is depicted schematically in FIG. 8. Due to the perfect spherical shape of ball lenses, the lens holder has preferably a rotational symmetry around the optical axis, which passes through the centre of the mounted lens. The ball lens of radius r is seated in a recess formed on the front major surface of the lens holder, this recess having preferably a conical shape. Suitable adhesive of composition well known in the art can be used for attachment of the ball lens to the holder. However, attachment of the ball lens is not limited to the use of an adhesive. For instance, the ball lens can also be held in place using a circular plate affixed to the side wall of the conical recess, this plate having a clearance hole of suitable diameter to allow free transmission of the light beam refracted through the ball lens. The tilt angle θ of the side wall of the conical recess is calculated from Eq. (3), and this angle thus depends upon the refractive index of the material from which the ball lens is made. Tilting the side wall according to the principle of the present invention allows the mounting of ball lenses of various diameters while keeping the lens' back focal plane always in the same position, as indicated by the vertical dashed line in FIG. 8. The minimum diameter for a ball lens to be mounted in such a holder is bounded by the diameter D_A of the clear aperture of the holder, while the maximum diameter of the ball lens depends on the thickness T of the holder. The lens holder as depicted in FIG. 8 preferably comprises a ring protruding outwardly from its back major surface. The flat surface of the protruding ring lies within the back focal plane of the lens mounted into the holder, which coincides with the trough of the conical recess as well. This flat surface acts as a reference plane for proper placement of either the exit aperture of a light emitting device or the input end of an optical fibre to be coupled to the mounted ball lens. People skilled in the art will readily recognise that several modifications to the above-described embodiment of a holder for spherical ball lenses can be made without departing from the scope of the present invention.

Referring to the basic principle of the invention, some intrinsic limitations in the use of a microlens holder fabricated according to this principle can be readily identified. As discussed above, the implementation of the invention requires cylindrical microlenses having a circular cross-section. This restriction therefore precludes the use of microlenses with aspheric or plano-convex shapes. It should be apparent, however, that this limitation is of minor consequence, owing to the widespread use of microlenses with circular cross-section. Along with the greater ease of manufacture, a circularly-shaped microlens also provides easier alignment steps since its rotationally-symmetric structure obviates the need for fine tuning of the rotation of the microlens around its longitudinal axis. A further limitation of the present invention is the need for microlenses whose back focal length is proportional to the radius (or diameter) of the microlenses. Likewise, this limitation does not restrict significantly the use of a holder fabricated according to the present invention because widely-used microlens designs for collimation of laser diode bars or arrays, that is, step-index and GRIN microlenses, exhibit such linear dependence of their back focal length.

The microlens array must be properly registered to the laser diode bar or array to be collimated in order to take full advantage of the appealing features offered by the present invention. As a result, the stringent manufacturing tolerances (in the μm range) which are of standard practice in this field must be maintained during the manufacturing and subsequent positioning of a microlens holder fabricated according to the invention. As for any other microlens holder to be set in front of a stacked laser diode array, the parallelism of the grooves formed in the holder as well as their relative spacing must be tightly controlled. Attention must be paid to the surface flatness of both sidewalls of the V-shaped grooves to ensure that the microlenses are correctly seated therein. The microlenses must exhibit sufficient stiffness when supported only by their ends to avoid mechanical deformations that could deviate the back focal plane of the microlens out of the plane of the front facet of the corresponding laser diode bar. Such mechanical deformations of the microlenses could lead to detrimental optical misalignment of the microlenses as well.

Although the present invention has been explained hereinabove by way of a preferred embodiment thereof, it should be pointed out that any modifications to this preferred embodiment within the scope of the appended claims is not deemed to alter or change the nature and scope of the present invention.

WHAT IS CLAIMED IS:

1. A microlens holder for supporting at least one microlens of circular cross-section in alignment with a light source, each of the at least one microlens having a radius and a back focal length varying linearly with said radius according to a gradient defining a positive constant factor k, the microlens holder comprising:

a base having at least one V-groove therein for receiving the at least one microlens, each of said at least one V-groove having a pair of side walls, both side walls being tilted by an angle θ relative to the plane of the emitting light source, said value of θ being defined by:

$$\theta = \cos^{-1}\left(\frac{1}{1+k}\right)$$

2. A microlens assembly comprising:

a microlens holder according to claim 1;

at least one microlens mounted into said at least one V-groove of the microlens holder; and

bonding means for bonding said at least one microlens to said V-groove.

3. A microlens assembly according to claim 2, wherein said bonding means comprise a glue.

4. A microlens assembly according to claim 2, wherein each of said at least one microlens is a cylindrical microlens.

5. A microlens assembly according to claim 4, wherein the base of said microlens holder comprises a pair of support members positioned parallel to each other, and the at least one V-groove comprises a pair of V-grooves for supporting portions of one of the at least one cylindrical microlens, the V-grooves of a pair respectively extending in each of the support members in alignment with each other.

6. A microlens assembly according to claim 2, wherein each of said at least one microlens is a ball microlens.

7. A microlens assembly according to claim 2, wherein the at least one microlens is made of a material having a uniform refractive index n, and k is defined by

$$k = \frac{(2-n)}{2(n-1)}$$

8. A microlens assembly according to claim 7, wherein said material is fused silica, and k has a value of about 0.5.

9. A microlens assembly according to claim 2, wherein the at least one microlens comprises a graded index microlens, and k has a value of about 0.37.

10. A microlens assembly according to claim 9, wherein said graded index microlens is a nonfull aperture Luneberg-type lens.

11. A microlens assembly according to claim 9, wherein said graded index microlens is a full aperture Luneberg-type lens.

12. A microlens assembly according to claim 10 or 11, wherein said graded index microlens has a homogeneous cladding.

13. A microlens assembly according to claim 10 or 11, wherein said graded index microlens has a non-homogeneous cladding.

14. A microlens holder for supporting at least one ball microlens in alignment with a light source having an optical axis, each of the at least one ball microlens having a radius and a back focal length varying linearly with said

radius according to a gradient defining a positive constant factor k, the microlens holder comprising:

a base having at least one recess therein for receiving the at least one microlens, each of said at least one recess having a conical side wall symmetrical around the optical axis and tilted by an angle θ relative to the plane of the emitting light source, said value of θ being defined by:

$$\theta = \cos^{-1}\left(\frac{1}{1+k}\right)$$

15. A microlens holder according to claim 14, wherein said at least one recess is formed in a front major surface of said microlens holder.

16. In combination, use of a microlens assembly as described in claim 2, and a laser diode array, for conditioning light emitted by said laser diodes along a slow axis thereof.

17. In combination, use of a microlens assembly as described in claim 2, and a laser diode array, for conditioning light emitted by said laser diodes along a fast axis thereof.

18. In combination, use of two microlens assemblies, each as described in claim 2, the microlenses of one holder being perpendicular to the microlenses of the other holder, both assemblies being used for conditioning light along both a fast and a slow axis of a laser diode array.

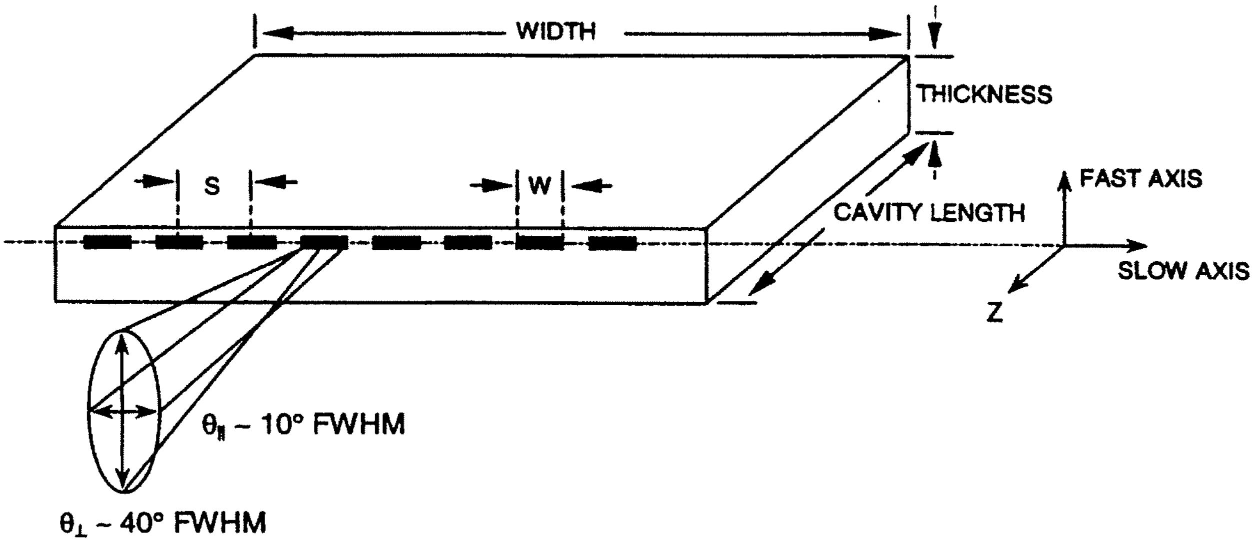


FIG. 1

(PRIOR ART)

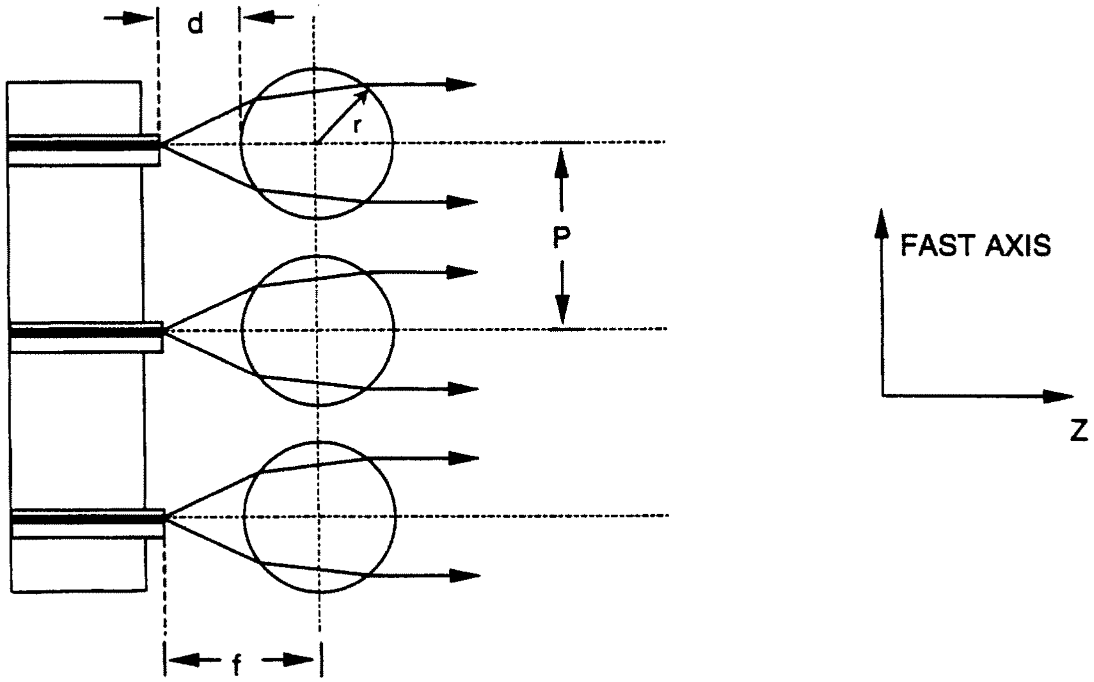


FIG. 2

(PRIOR ART)

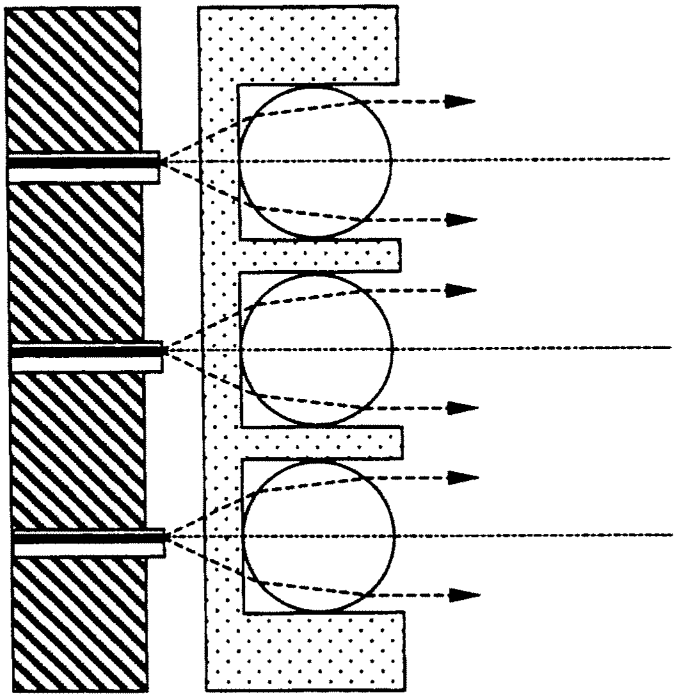


FIG. 3

PRIOR ART

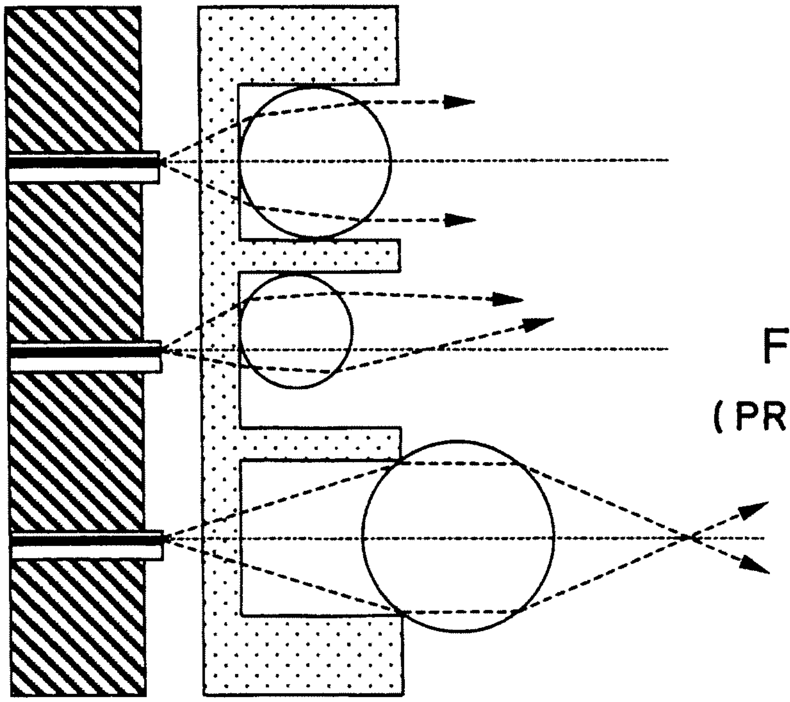


FIG. 4

(PRIOR ART)

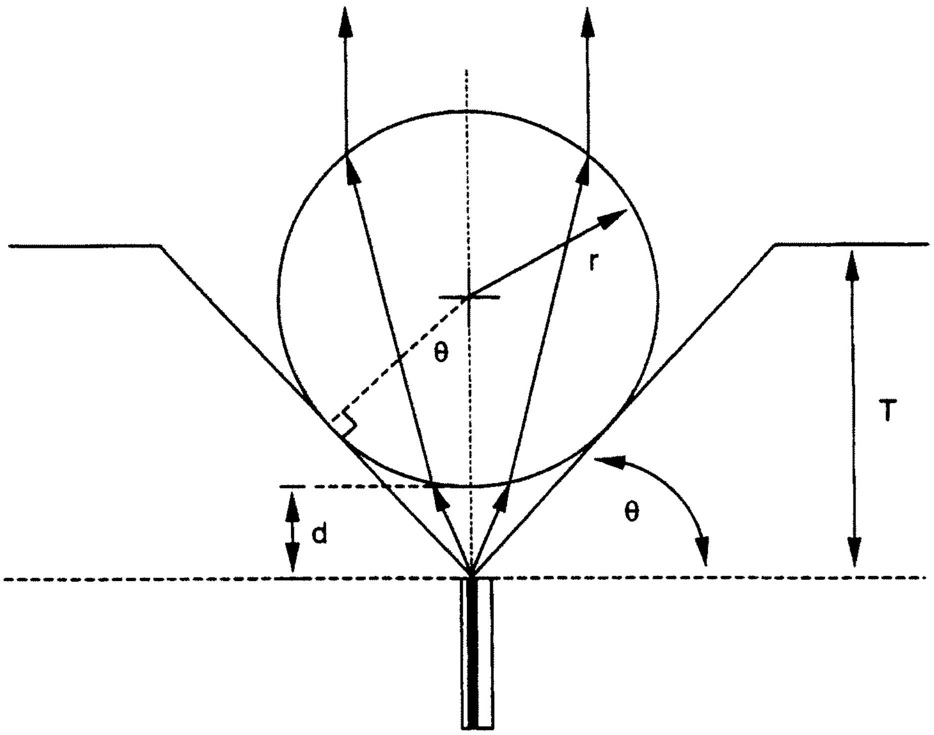


FIG. 5

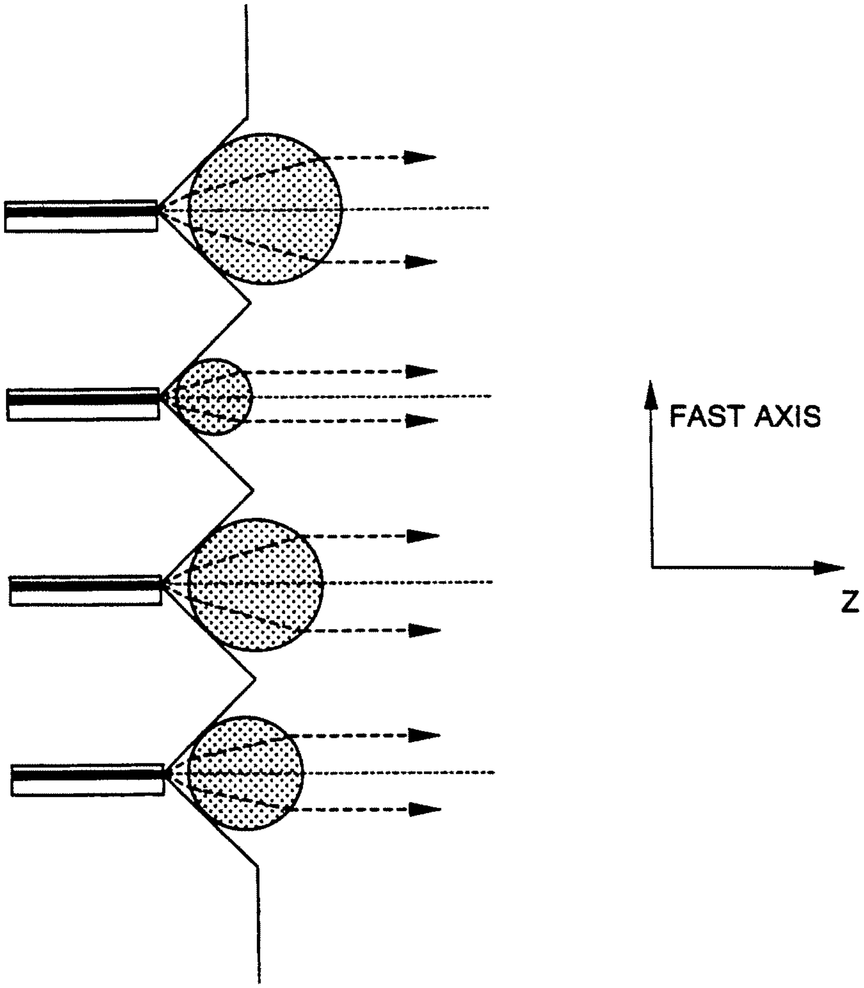


FIG. 6

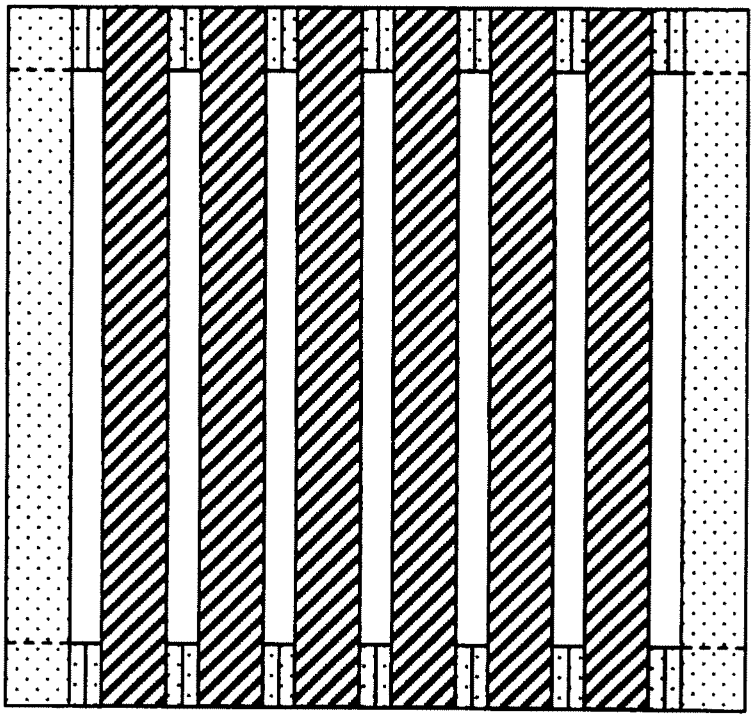


FIG. 7A

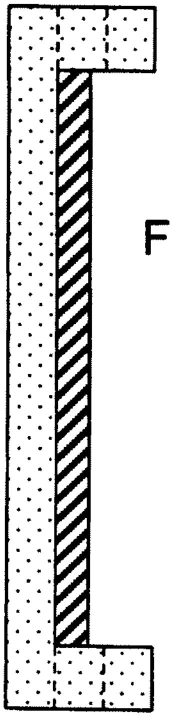


FIG. 7C

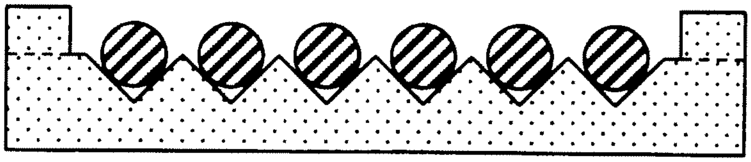


FIG. 7B

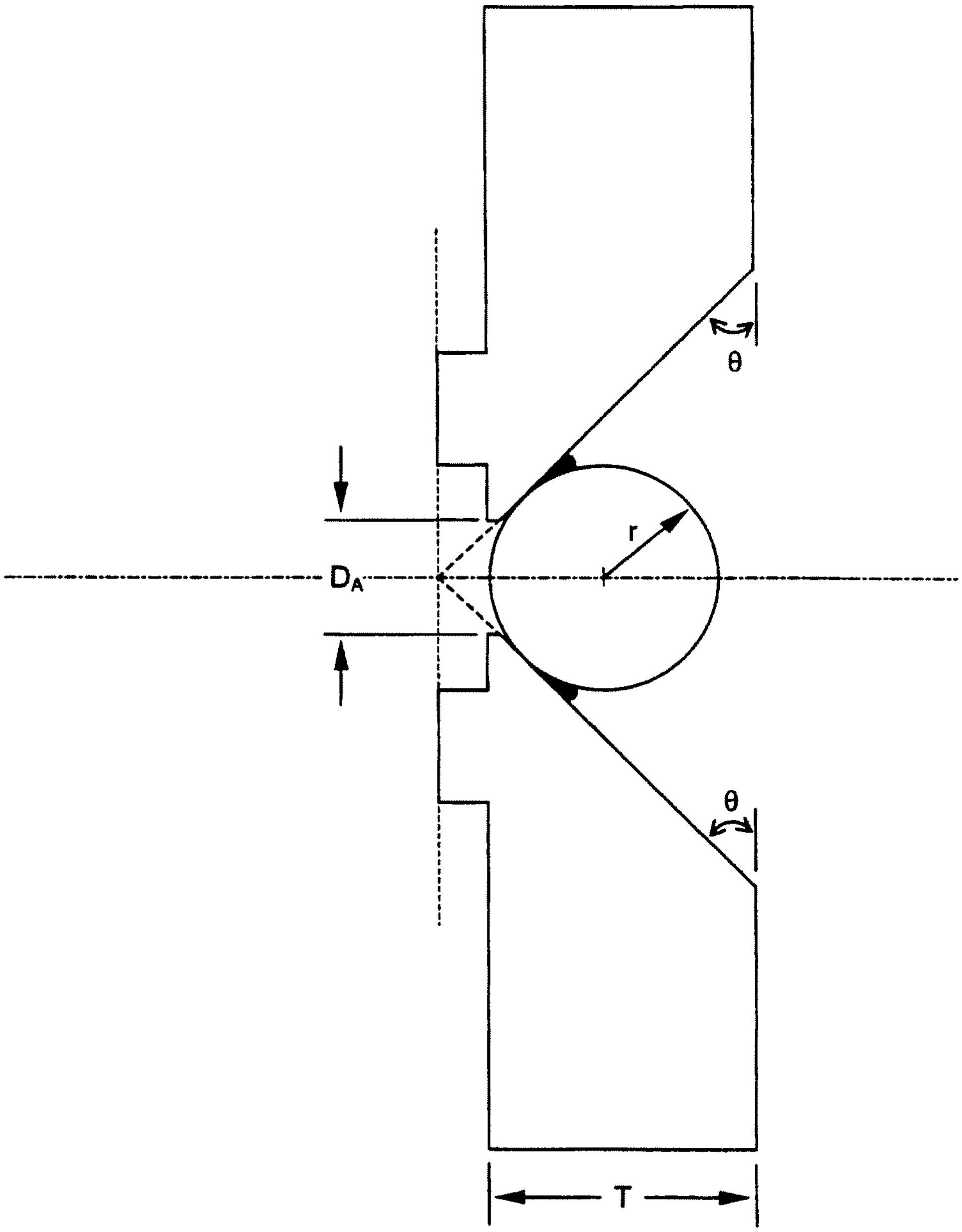


FIG. 8