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PATENT SPECIFICATION

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(54) IMPROVEMENTS IN OR RELATING TO OPTICAL EQUALIZERS

(71) We, CSELT—CENTRO STUDI E LABORATORI TELECOMUNICAZIONI, S.P.A., of Via Guglielmo Reiss Romoli, 274, 10148 Torino, Italy, a joint stock company organized under the laws of Italy do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to optical signal transmission systems and particularly to optical equalizers for transmitting optical signals between consecutive portions of a multimode optical waveguide (e.g. Optical fibres, ribbons and thin films) having a stepped refractive index profile, and has particular application to the transmission of light signals in telecommunications.

It is known that a light signal travels through the core of an optical fibre as a plurality of rays forming a range of different angles with the fibre axis. The rays strike the wall of the core, where the refractive index changes abruptly, at various angles. At this wall the rays are totally reflected in accordance with the laws of reflection. It evolves that the various rays travelling through the fibre, cover optical paths of different lengths. The axial rays have a minimum path length and the rays forming the greatest angle with the axis of the fibre (referred to herein as the maximum guidance angle rays) cover the maximum path length. The result of such a difference in path lengths gives rise to a widening of the signal.

In fact, in any cross section of the fibre, it is found that a signal generated by a generator at one end of the fibre as a theoretically instantaneous pulse (Dirac pulse) has a finite width which increases with increase in the distance of the examined section from the pulse generator.

Over long distances this widening of the signal is the main reason why, in this type of fibre, the band of transmissible frequencies is considerably restricted. In fact the repetition frequency of the generated optical signals has to be correlated to the width the signals will present at their arrival in the receiver in order to avoid interference between consecutive signals.

To try to overcome this problem, several devices called equalizers have already been proposed.

A first type of equalizer proposed was electronic and operated on the received signal. In this type of equalizer, rays received at different angles to the waveguide axis, were electronically detected as belonging to discrete angle ranges and the resulting signals were passed through suitable delay lines, whose delays were respectively dependent on the associated angle ranges. In theory, such an equaliser is capable of reducing the width of the signal by 90%. However, this electronic type of equalizer has been generally rejected for practical purposes due to difficulties of design and maintenance and has been superseded by various proposals for optical equalizers.

Equalizers of the optical type that have been proposed comprise converging lenses of various shapes which refract the light rays incident at various angles in accordance with the well known laws of refraction. The common principle applied in equalizers of this type is that rays making an angle zero with the axis of the optical waveguide (i.e., axial rays), are converted into rays forming the maximum guidance angle with the axis of the optical waveguide and maximum guidance angle rays are converted into axial rays, so compensating, through this exchange, the difference in optical path length. These proposed equalizers present the common characteristic of equalizing exactly only the rays covering the longest and shortest paths, that is axial rays and maximum guidance angle rays; the intermediate angle rays are not taken into account and as a consequence they are not equalized. The most significant consequent of this partial equalization is that the width of the received pulse is only reduced by 75% of the width it would have without equalization; this reduction may be adequate when the transmission is not over very long distances, or when the original band of transmissible frequencies is not very wide; otherwise the resulting width of the received signal still poses serious problems.

According to this invention there is provided an optical signal transmission system comprising two multi-mode light guides of stepped refractive index profile with confronting ends aligned on a common centreline and respectively for emitting and collecting bundles of light rays within a characteristic maximum guidance angle θ_m which is sufficiently small that $\theta_m \approx \tan \theta_m$, and an optical equaliser located between said confronting ends and comprising first and second refractive interfaces respectively spaced from the proximal confronting light-guide end by a distance s and mutually spaced apart along said common centreline by a distance d, said equaliser having a focal length at each of said interfaces which varies as a function f(r) of the distance r from said common centreline in accordance with the equation

$$\frac{1}{f(r)} = \frac{1}{s} + \frac{1}{d}\left[1 \pm \sqrt{\frac{s^2}{r^2}\theta_m^2 - 1}\right] \qquad (5)$$

Embodiments of this invention will now be described, by way of examples only, with reference to the accompanying drawings wherein:—

Fig. 1 is a schematic diagram illustrating the generic behaviour of light rays passing through an optical equalizer embodying the invention;

Fig. 2 is a diagram representing contours of lenses forming an equaliser embodying the invention;

Fig. 3 is a schematic diagram illustrating the behaviour of light rays passing through an equalizer employing lenses having the contour of curve A in Fig. 2;

Fig. 4 is a schematic diagram illustrating the behaviour of light rays passing through an equalizer employing lenses having the contour of curve B in Fig. 2;

Figs. 5 and 6 are schematic diagrams showing the cross-sections of systems of lenses of equalizers embodying this invention and respectively employing lenses whose cross-sectional profiles are as denoted by the curves A and B in Fig. 2;

Figs. 7 and 8 are schematic diagrams showing the cross-sections of systems of lenses of equalizers forming respective variants of the embodiments shown in Figs. 5 and 6; and

Fig. 9 is a schematic diagram showing the cross-section of an equalizer comprising a refractive body having a graded index profile and embodying this invention.

The construction and operation of equalizers embodying the present invention may be appreciated from theory forming the basis of the invention and which gives rise to the contours shown in Fig. 2. This theory will now be described briefly, with reference to Fig. 1.

It has been stated ("Optical Equalizer for Multimode Optical Fibres" by P. Di Vita, R. Vannucci, paper presented at the "XXIII Rassegna Elettronica Nucleare ed Aerospaziale", Rome, March 18—28, 1976) that, denoting by θ (Fig. 1) the angle formed with the axis of the system shown schematically in Fig. 1 (that is, the axis common to the two waveguide portions g and g' and to lenses L and L′ forming the refractive interfaces of the equalizer) by a generic ray emerging from a first waveguide portion g, denoting by θ' the angle formed with said axis bv the ray a" emerging from the second lens L′ and corresponding to the ray a, and denoting by θ_M the maximum guidance angle of the waveguide, exact equalization of the optical path lengths of the rays is obtained when the equation:—

$$\sec\theta + \sec\theta' = 1 + \sec\theta_M$$

is satisfied.

Denoting by w the portion of the lens L subtended by maximum guidance ray b and by s the distance from the terminal point P of the waveguide portion g from lens L, we obtain the elementary equation:—

$$w = s \tan\theta_M$$

Taking into consideration that, in order to convey a lot of information, the optical fibres generally used in telecommunications have small values of Θ_M such that $\theta_m \approx \tan\theta_m$ (low-guidance fibres), we have:

$$\theta_M << 1 \text{ rad}$$

Condition (3) enables the use of the well known relationship

$$\sec\theta \simeq 1 + \frac{\theta^2}{2}$$

which converts equation (1) into

$$\theta^2 + \theta'^2 = \theta^2_M$$

and equation (2) into:

$$w \simeq s\,\theta_M$$

from which $w << s$ is obtained.

Moreover, denoting by r the portion of the lens L subtended by the generic ray a and by r' the portion of the lens L' subtended by the corresponding ray a'', and assuming that the second waveguide portion g' is at the same distance s from the second lens L', then:—

$$r = s\tan\theta, \text{ that is, } r \simeq s\,\theta;$$

$$r' = s\tan\theta', \text{ that is, } r' \simeq s\theta'.$$

If $f(r)$ denotes the function describing the variable focal length of the lenses, (a function of r) it can be demonstrated that, in order to implement equation (4) in a system of two identical refracting lenses coaxial with consecutive fibre portions, spaced by distance d, the variable focal length function must satisfy the relationship

$$\frac{1}{f(r)} = \frac{1}{s} + \frac{1}{d}\left[1 \pm \sqrt{\frac{s^2\,\theta^2_M}{r^2} - 1}\right] \qquad (5)$$

where the variation range of r is $0 \leqslant r \leqslant w$.

It can be noted that, with variable focus lenses satisfying equation (5) with the sign "+" in front of the square root, the light rays have paths as illustrated in Fig. 3.

In Fig. 3, it can be seen that rays incident on the first lens L, and belonging for instance to the upper half plane with respect to the axis of the system, are refracted giving rise to rays which meet each other in pairs between the two lenses.

With variable focus lenses satisfying equation (5) with the sign "−" in front of the square root, the paths of the light rays are as illustrated in Fig. 4 from which it may be seen that rays incident on the first lens and belonging, for instance, to the upper half plane with respect to the axis of the system, are refracted giving rise to rays between the two lenses which never meet with each other.

Equation (5) renders it possible to determine contours of the lenses to form the equalizer once it has been decided what type of lens one intends to use, that is, plano-convex, symmetrical biconvex or asymmetrical biconvex.

Various technical factors relating to the feasibility of the lenses, favour making use of plano-convex lenses.

In this case, the law defining the contour $z(r)$ of the convex part of lens whose refractive index is denoted by n, is obtained from equation (5).

The following equation can be obtained:

$$z(r) = -\frac{1}{n-1}\left[\frac{r^2}{2s} + \frac{r^2}{2d} \pm \frac{1}{2d}\left(r\sqrt{(s\theta_M)^2 - r^2} + (s\theta_M)^2 \arcsin\left(\frac{r}{s\,\theta_M}\right)\right)\right] + \text{const.} \qquad (6)$$

Equation (6) provides two contours, one corresponding to having the sign "+", between the second and the third terms within square brackets, and the other corresponding to having the sign "−" between these terms.

The occurrence of these signs corresponds to the occurrence of the signs "+" and "−" in equation (5) and depending on the choice of sign, the resulting lenses cause light rays to follow paths either as shown in Fig. 3 (sign "+") or as shown in Fig. 4 (sign "−").

A graph of equation (6) is given in Fig. 2, where curve A denotes the contour obtained from equation (6) with sign "+", and curve B denotes the contour obtained from equation (6) with sign "−".

Curves A and B shown in Fig. 2 indicate the contours only for one of the semiplanes into which the axis of the system (Fig. 1) splits the plane.

The general theory outlined above gives rise to different practical embodiments.

A first embodiment is obtained by placing two plano-convex lenses R and R′ in spaced parallel planes perpendicular to the axis of the system, each lens having a cross-section as shown in Fig. 5. The two lenses R and R′, have a plane surface VPV′ and a convex surface VOV′ where contour VO is identical to contour OV′, and corresponds exactly to curve A shown in Fig. 2.

The equalizer shown in Fig. 5 corresponds to the arrangement shown in Fig. 3, where lines L and L′ are replaced by lens cross-sections as shown in Fig. 5; light rays passing through the equalizer follow the paths indicated in Fig. 3.

When the optical waveguide is a circular cross-section fibre, the two lenses R and R′ (Fig. 5) are each symmetrical in space about the axis OP of the system, and so each lens has a semi-pseudo toroidal shape and the plane surface of the lens will be circular.

When the optical waveguide is a thin ribbon in which the scattering of light rays takes place only in the direction of the greater cross-sectional dimension of the ribbon, the two lenses R and R′ will each by symmetrical in space with respect to a plane containing the axis OP and perpendicular to the plane of the drawing.

The result is that for lenses having a plano-pseudo-bicylindrical shape, the ribbon is positioned with its greater cross-sectional dimension (that is, in the direction of the ray scattering) orthogonal to the symmetry plane, that is, orthogonal to the generatrices of the pseudo-cylinders. The plane surface of each such lens is a rectangle.

A second embodiment is obtained using two plano-convex lenses H and H′ which are again placed in spaced parallel planes perpendicular to the axis of the system and have each a cross-section as shown in Fig. 6. The two lenses H and H′, each have a flat surface CEC′ and a convex surface CDC′, and contour CD is identical to contour DC′ and corresponds exactly to the curve B shown in Fig. 2.

From the point of view of operation, the equalizer corresponds to the arrangement shown in Fig. 4, where lines L and L′ are replaced by the lenses H and H′ and light rays follow the paths shown in Fig. 4.

In the case where the optical waveguide portions are circular cross-section fibres the two lenses H and H′ (Fig. 6) are each symmetrical in space with respect to the axis DE (which is the axis of the system) and so each lens has a plano-cuspidal shape.

In the case where the optical waveguide portions are thin ribbons, the two lenses H and H′ are each symmetrical in space with respect to a plane containing axis DE and perpendicular to the plane of the drawing. The result is that for lenses each having a plano-pseudo-cylindrical shape, with a cross-section as shown in Fig. 6, the thin ribbons will each be placed with its greater cross-sectional dimension, (that is, in the direction of ray scattering) orthogonal to the generatrices of the pseudo-cylinder.

Another embodiment of the invention is obtained using Fresnel lenses each of whose contours is interrupted by a plurality of grooves separating tooth contours of the lens. In this case, equation (6) makes it possible to obtain the shape of the contour $Z'(r)$ to be presented by the m-th groove. If a number M of grooves, increasing with the degree of perfection required for the equalization, is chosen for the Fresnel lens, the following equation is obtained:

$$Z'(r) = z(r) - z\left(\frac{m}{M} w\right) \qquad (7)$$

where the range of r for each groove is:

$$\frac{m-1}{M} w \leqslant r \leqslant \frac{m}{M} w$$

Function z present in equation (7) is the same function z as in equation (6) and entails the double solution provided by the signs "+" and "−", which thus determine the possible shapes for the Fresnel lenses. Considering equations (6) and (7) to have the sign "+", the Fresnel lens has a tooth contour corresponding to curve A shown in Fig. 2; considering the equations (6) and (7) to have instead the sign "−", the resulting Fresnel lens has a tooth profile corresponding to curve B shown in Fig. 2.

By taking into account what is stated above about the choice of a system having two converging, parallel, plano-convex lenses having a common axis aligned with the axes of the optical waveguide portions, it is easy to determine the lens systems whose cross-sections are schematically represented in Figs. 7 and 8. Fig. 7 shows lenses whose tooth contours correspond to curve A shown in Fig. 2 and Fig. 8 shows lenses whose tooth contours correspond to curve B shown in Fig. 2. Light ray paths will correspond, for the embodiment shown in Fig. 7 to the arrangement shown in Fig. 3, and, for the embodiment shown in Fig. 8, to the arrangement shown in Fig. 4.

When the optical waveguide portions are circular cross-section fibres the lenses K, K′ (Fig. 7), X and X′ (Fig. 8) are each symmetrical in space with respect to the system axis (FG or NQ) and the convex surface is formed with a series of concentric rings and each ring has a contour as given by equation (7).

When the optical waveguide portions are thin ribbons, each of the lenses K K′, X and X′ are pseudo-cylindrical and symmetrical in space with respect to a plane containing the system axis (FG and NQ) and perpendicular to the plane of the drawing. The result is that the ribbon is again placed with its greater cross-sectional dimension orthogonal to the generatrices of the pseudo-cylinders, the surfaces of the lenses each have rectangular straight grooves between tooth contours as given by equation (7).

Embodiments of the invention can be realized by means of recent holography techniques.

In particular, the refractive interfaces schematized in Figs. 3 and 4 by lines L and L′, can, instead of being lenses as in the previous embodiments, be two holograms on which the contours of the lenses of Fig. 5 (or Fig. 6) are recorded.

It is known that a hologram acting as a lens may be recorded by means of a lens. Thus some of the difficulties in making the lenses described above may be overcome by making use of the construction of "hologram-records". Holograms so recorded have the same effect on the incident light-rays as the lenses 5 and 6, and so for this type of embodiment also the considerations stated above as applying to the cases of circular fibres and thin ribbons remain valid. Suitable recording of the holograms is readily achieved taking these considerations into account.

It should be noted that such holograms cause losses so that they should only replace the lenses in the above-described embodiments when the available energy in the fibre is such as to allow such losses.

Finally, embodiments of the invention may be achieved using a graded-refractive-index transparent body the end faces of which form the refractive interfaces of the equaliser.

It is known that recent techniques in the production of optical fibres, have enabled the making of cylindrical transparent bodies (small bars, wires) having a graded refractive index profile in which the refractive index varies along the cylinder radius. More particularly, the so-called CVD (Chemical Vapour Deposition) technique which has been developed enables the making of cylindrical bodies whose refractive index variation is a continuous function of the radius of the body. A cylinder having a refractive index which varies along the radius in accordance with any law can be obtained by such a technique.

This technique can also be used to make transparent ribbons having a refractive index which varies along one of the Cartesian axes of the cross-section, for instance the axis of the greater cross-sectional dimension, while having a constant refractive index along the second axis.

Such a body, whether cylindrical or ribbon-shaped, is herein referred to as a "graded-index body". The length of the body is determined by the condition that all the rays emerging from the first waveguide portion g (Fig. 1) are conveyed, at the output from said graded index body, to the terminal of the second waveguide portion g'.

It has been hypothesised and confirmed experimentally that a system of lenses having determined optical characteristics, can be replaced by an equivalent graded-index body arranged to process incident light rays in the same way as the system of lenses being replaced.

In the present case, each system of lenses, such as the one shown in Fig. 5, is well-defined since equation (6) which determines the convex contour $z(r)$ of each of the lenses as a function of the lens spacing d, of the distance s of each of the lenses from the end of the adjacent optical waveguide portion and of the maximum guidance angle θ_M of the waveguide portions. It is then possible to obtain by mathematical processes, a function $n(r)$ determining the variation of the refractive index inside the graded-index body so as to make it equivalent to the system of lenses that is to be replaced.

In this kind of embodiment the external geometry of the equalizer is the same whether the refractive index $n(r)$ is obtained from equation (6) taken with the sign "+" between the second and third terms inside the square brackets, or from the same equation taken with the sign "−" instead of the sign "+".

This type of equalizer is schematically represented in Fig. 9, where S′ is a section through the graded-index body. Clearly two different embodiments will result depending on whether the law of variation of the refractive index of the graded-index body corresponds to the system shown in Fig. 5 or the system shown in Fig. 6.

When the optical waveguide portions are circular cross-section fibres the graded-index body is a right cylinder having a radius at least as great as w (Fig. 1) and a length d determined in accordance with the criteria established for the equivalent lens system.

When the optical waveguide portions are thin ribbons the graded-index body is a right parallelepiped rectangular in cross-section and having a refractive index which varies in the direction of the greater dimension of the cross-section (side y in Fig. 9) and remains constant along the direction orthogonal to the greater cross-sectional dimension in the plane of the section. For the other dimensions, the considerations stated above for the cylindrical body are still valid.

It will be appreciated that in making an equalizer in accordance with one of the embodiments described above, the lens arrangement can be made and supplied separately from the waveguide portions, the lens arrangement being characterized by the function describing the focal length variation of each lens, this function being dependent on predetermined values of distance between waveguide portions and maximum guidance angle that will characterise the arrangement of consecutive waveguide portions with which the equalizer can be used.

However, in general, the realization of all the embodiments preferably involves the provision of some common features.

The optical system and the terminal portions of the optical waveguide portions are preferably embedded in a block of transparent material (not shown in the drawings), having the same refractive index as the core material of the optical waveguide portions.

Moreover, when the equalizer is built for thin ribbon waveguides, so that the equalization is required only in one direction, two reflecting slabs parallel to the plane of scattering should be provided. These slabs are spaced by a distance equal to the minimum size of the ribbon, in such positions as to act as extensions of the cladding of the ribbon. The longitudinal sections of these slabs, parallel to the axis of the system, are denoted by T in Fig. 9.

It will be clear to those skilled in the art that there are various modifications that can be made to the embodiments described above.

For instance, the lenses forming the system may have a refractive index less than that of the surrounding medium and in this case the lenses each have a plano-concave shape, and the curved contours will correspond to one of the two solutions of equation (6). If other kinds of lenses derived from equation (5) are used, it is sufficient to derive from this equation suitable contours for both symmetrical and asymmetrical bi-concave lenses.

It will be appreciated that the embodiments described above enable complete equalization of the rays being transmitted in that there is equalization of rays leaving the waveguide portion at all angles between zero and the maximum guidance angle θ_M. Also it is to be noted that the equalizer requires no more than two refractive interfaces (lenses in the case of lens systems so that energy losses due to refraction can be minimised. It will be clear from the embodiments described above that there is substantial versatility available in determining the kind of equalizer to be provided in dependence on the characteristics of the transmission line and the technology available.

WHAT WE CLAIM IS:—

1. An optical signal transmission system comprising two multi-mode light guides of stepped refractive index profile with confronting ends aligned on a common centre-line and respectively for emitting and collecting bundles of light rays within a characteristic maximum guidance angle θ_m which is sufficiently small that $\theta_m \approx \tan \theta_m$,

and an optical equaliser located between said confronting ends and comprising first and second refractive interfaces respectively spaced from the proximal confronting light-guide end by a distance *s* and mutually spaced apart along said common centreline by a distance *d*, said equaliser having a focal length at each of said interfaces which varies as a function f(r) of the distance *r* from said common centreline in accordance with the equation

$$\frac{1}{f(r)} = \frac{1}{s} + \frac{1}{d}\left[1 \pm \sqrt{\frac{s^2}{r^2}\theta_m^2 - 1}\right]$$

2. A system according to claim 1, wherein each asid interface is formed by a body of refractive index *n* which, when viewed in cross-section has the profile of two lenses each with a curved contour which varies as a function Z(r) of the distance r, in accordance with the equation

$$Z(r) = \frac{-1}{n-1}\left[\frac{r^2}{2s} + \frac{r^2}{2d} \pm \frac{1}{2d}\left(r\sqrt{s^2\theta_m^2 - r^2} + s^2\theta_m^2 \arcsin\frac{r}{s\theta_m}\right)\right] + \text{constant}$$

3. A system according to claim 2, wherein said lenses are plano-convex, plano-concave, biconvex or biconcave.

4. A system according to claim 1, wherein each said interface is formed by a hologram in which there is recorded a pair of lens profiles each with a curved contour which varies as a function Z(r) of the distance *r*, in accordance with the equation

$$Z(r) = \frac{-1}{n-1}\left[\frac{r^2}{2s} + \frac{r^2}{2d} \pm \frac{1}{2d}\left(r\sqrt{s^2\theta_m^2 - r^2} + s^2\theta_m^2 \arcsin\frac{r}{s\theta_m}\right)\right] + \text{constant}$$

5. A system according to claim 2 or claim 4, wherein said lenses are Fresnel lenses and each tooth contour is defined by a function Z′(r) where

$$Z'(r) = z(r) - z\left(\frac{m}{M}w\right)$$

m being the order number of the tooth contour
M the total number of tooth contours
$w = s \tan\theta_m$, and

r is in the range $\frac{m-1}{M}w \leqslant r \leqslant \frac{m}{m}w$

6. A system according to claim 1, wherein said interfaces are formed by the ends of a graded-index body whose refractive index varies as a function n(r) derived from the function f(r).

7. A system according to any preceding claim, wherein said light guides are of circular cross-section and for each said interface the function f(r) has circular symmetry about said common centreline.

8. A system according to any one of claims 1—6, wherein said light guides are thin ribbons exhibiting multimode behaviour over their greater cross-sectional dimensions and for each said interface the function f(r) applies only in planes normal to the plane containing said common centreline and normal to the greater cross-sectional dimension of the light guides.

9. A system according to claim 8, wherein internally-reflecting planar surfaces extend between said confronting light guide ends as extensions of the cladding of said thin ribbons at the lesser cross-sectional dimensions of the light guides.

10. An optical signal transmission system substantially as hereinbefore described with reference to any one of the embodiments of the accompanying drawings.

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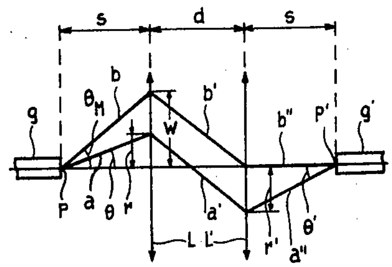

Fig. 1

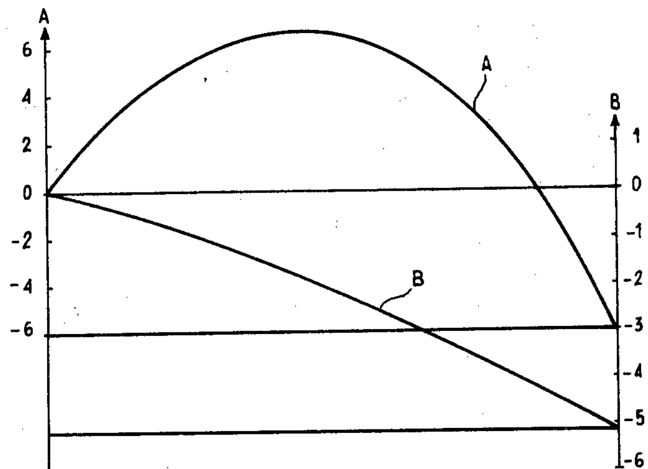

Fig. 2

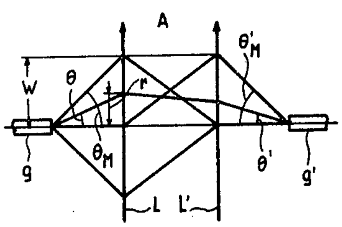

Fig. 3

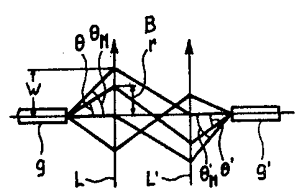

Fig. 4

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2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 2

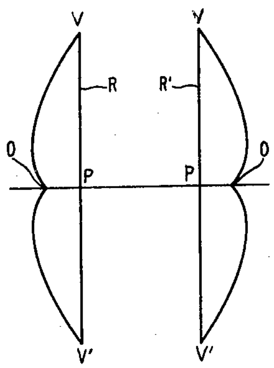

Fig. 5

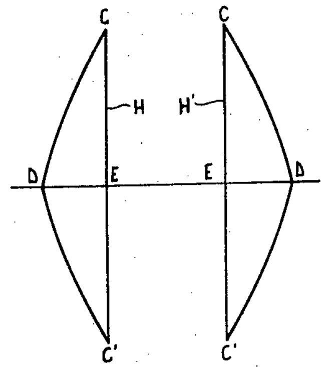

Fig. 6

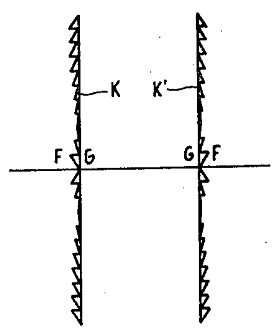

Fig. 7

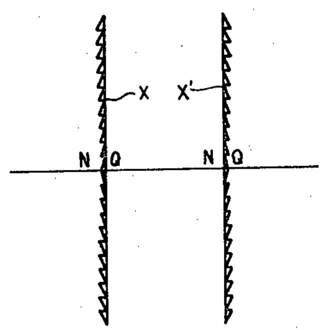

Fig. 8

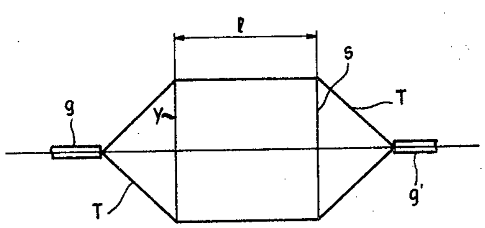

Fig. 9