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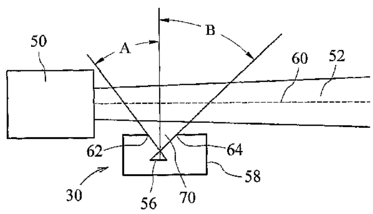
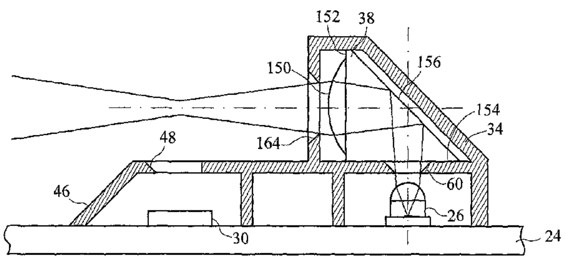
(54) **Title:** SMOKE DETECTOR





(57) **Abstract:** A smoke detector has a light sensor positioned such that a light-receiving surface of the sensor extends generally parallel to a light beam generated by a SMD LED light source of the smoke detector. The light sensor has an enclosure surrounding the light-receiving surface, which enclosure has an aperture in a side facing the light beam. The front and rear edges of the aperture (with reference to the direction of the light beam), are positioned to create a balance of sensitivity to forward-scattered pale-coloured smoke and backward-scattered dark-coloured smoke. The use of a SMD LED in. association with a proximate means for redirecting and refocusing light allows for construction of a compact low-profile smoke detector. The SMD LED may be a laser diode.

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SMOKE DETECTOR

The present invention relates to a smoke detector, and in one aspect to a light sensor for detecting light scattered from smoke particles in such detector, and in another aspect to a compact light source for the detector.

In smoke detectors based on sensing light scattered from a light beam by smoke particles, the light scattered onto a sensor is a tiny fraction of the total light emitted by a source of the light beam. The fraction depends on the smoke density, and typically is in the order of 0.001% at the alarm point of a general-purpose fire detector. Reliably sensing such a signal is difficult. It is therefore highly desirable to design the smoke detector so as to maximize the amount of scattered light falling on the light sensor.

One way to achieve such aim is to increase the amount of energy emitted by the light source. However, this has two disadvantages. Firstly, it requires that the operating power of the smoke detector be increased. Secondly, it reduces the lifespan of the light source. Because of these disadvantages, it is preferable to improve the amount of scattered light falling on a light sensor by, if possible, improving the light collection efficiency of the light sensor through passive means.

A further aim in the design of smoke detectors is to achieve a light-sensor response that is uniform for a range of smoke colours and types. It is known that pale-coloured smoke ('pale smoke') produced by smouldering fires gives higher levels of scattered light than the dark-coloured smoke ('dark smoke') produced by flaming fires. It is also known that the fraction of light scattered in different directions varies with the colour of the smoke. Pale smoke and liquid aerosols entering a light beam will cause light in the light beam to scatter predominantly in forward directions, i.e. those directions having a component that is parallel to the light beam and in an outward direction (away from the light source); on the other hand, dark smoke will cause light to scatter proportionally more in directions with a component that is parallel to the light beam and in an inward direction (toward the light source). The two foregoing types of scattered light are hereafter respectively referred to as 'forward-scattered light' and 'backward-scattered light'.

Most smoke detectors presently available are able to sense forward scattered light, and are designed to maximize the amount of such light sensed. As a result, most such detectors have a poor response to dark smoke relative to their response to pale smoke.

In regard to either forward-scattered light or backward-scattered light, the amount of scattered light reduces with an increase in the angle formed with the direction of the light beam. Thus the amount of scattered light is at a minimum in a direction normal to the direction of the light beam. Moreover, in such normal direction the difference in the level of scattered light produced by pale smoke and that produced by dark smoke tends to be at a minimum. There is thus the advantage in measuring the scattered light extending normal to the light beam in that a uniform response to different-coloured, i.e. both pale and dark, smoke entering the light beam is possible. However, since the scattered light is at a minimum in the normal direction to the light beam, the design of a suitable light sensor for sensing in such normal direction is difficult.

An object of a first aspect the preferred embodiment of the present invention is to control the relative sensitivity of the detector to pale and dark smoke. Usually this will be achieved in an arrangement in which the axis of the sensor is normal to the axis of the light beam, but need not always be so provided allowance is made in the characteristics of the sensing circuitry eg. based on calibration of prototypes.

Another object is to achieve an optical arrangement that is compact, so as to facilitate a smoke detector with a low-profile design.

The light sensor of a first aspect the subject invention is intended to detect and also to detect forward-scattered light and backward-scattered light each extending within a respective defined angle on a respective opposite side of a normal to the light beam; the sum of the two defined angles is termed 'the sensor acceptance angle'.

The subject invention in its first aspect is a smoke detector having a light sensor, the light sensor being positioned such that its optical axis extends transversely of (and preferably generally perpendicular to) a light beam generated by a light source of the smoke detector, the sensor having first and second light shields positioned between the light beam and the light-receiving surface for defining the directions from which scattered light from smoke particles in the light beam can strike the light-receiving surface, the position of the shields being chosen in accordance with a desired ratio of forward scattered light striking the light-receiving surface to backward scattered light striking that surface.

Preferably, the first and second light shields are formed as a first pair of opposed edges of an aperture, the aperture being positioned between the light beam and the light-receiving surface, light scattered from smoke in the light beam passing to the light-receiving surface through the aperture.

Preferably, the light shields are positioned relative to the light-receiving surface such that light scattered from the light beam strikes the light-receiving surface at an angle of incidence of 45° or less.

Preferably, the light shields are positioned relative to the light-receiving surface such that the maximum angle of incidence at which the backward-scattered light strikes the light-receiving surface is greater than the maximum angle of incidence at which the forward-scattered light strikes that surface.

Preferably, a said light shield has an operative edge that extends generally normal to the axis of the light beam.

Preferably, the light shields have a pair of opposed operative edges that are, at least in part, not parallel to each other.

Preferably, the opposed edges diverge from each other with distance from the axis of the light beam.

Preferably, the detector has a pair of second light shields extending generally parallel to the axis of the light beam. More preferably, each of the second light shields has an edge which is approximately on a line extending between a respective side boundary of the light beam and a respective corresponding side edge of the light-receiving surface.

Preferably, the aperture is defined by a frame formed as part of an enclosure surrounding the light-receiving surface.

Preferably, there are a plurality of light-receiving surfaces each having a respective field-of-view defined by the light shields. More preferably, the plurality of light-receiving surfaces are distributed parallel to the axis of the light beam.

Preferably, the or each light-receiving surface is a photodiode. More preferably, the plurality of light-receiving surfaces are formed by discrete photodiodes, or are formed by photodiodes within the same package in the form of a linear array. Preferably, each photodiode is a silicon Positive-Intrinsic-Negative (PIN) photodiode.

Preferably, the light shields are spaced approximately

3mm from the longitudinal axis of the light beam.

Preferably, the light-receiving surface is spaced 10mm or less from the axis of the light beam.

Preferably, the light-receiving surface is spaced 8mm or less from the axis of the light beam.

Preferably, the light-receiving surface is spaced 6mm or less from the axis of the light beam.

Preferably, the smoke detector has a base, a cover mounted for covering the base, and a circuit board carrying the light source, and wherein, when the cover is covering the base, the base and cover together define an internal chamber adapted to house the circuit board and to receive smoke but to block external light. More preferably, a background light level in the internal chamber is less than 10% of a signal of the light beam at 3%/ft obscuration.

Preferably, the smoke detector also includes a cylindrical condenser lens positioned between the light beam and the light-receiving surface, the axis of a cylindrical surface of the lens extending parallel to the axis of the light beam.

Turning to the second aspect of the invention, scattered-light smoke detectors normally use a light-emitting diode (LED) as their light source because of the low cost and high reliability of LEDs. In a typical such detector, a light source and light sensor are arranged to function within a dark optical chamber such that there is no direct line of sight between them, but such that their respective emission and reception fields intersect at a point inside the chamber. In such an arrangement, one of the practical difficulties is to minimize the amount of stray light from the light source that reaches a receiving surface of the light sensor.

The largest contribution to stray light is reflections from the chamber walls. Although the walls may be black, there is still a substantial amount of reflected light compared with the levels scattered from smoke. The easiest way to reduce the effect of such reflected light is to make the dimensions of the chamber quite large. However, that of course results in a detector of overall large size, which has the disadvantages of increased cost and reduced aesthetic appeal.

An alternative way to reduce the effect of reflected light is to use a light source with a narrow beam having small divergence, since the reflection from a narrow beam can be more easily controlled within a small optical chamber. This allows the detector size to be kept small.

The LEDs normally used in smoke detectors have polar emission patterns that have a very strong central lobe; such emission patterns are typically only 8° wide. Although a substantial portion of the light energy is contained within the central lobe, there always exist side lobes that can contribute significantly to the stray light inside the chamber. Such side lobes are normally blocked by one or more apertures placed in front of the LED. Unfortunately, the complete removal of the side lobes is very difficult unless a series of aperture stops is used. However, inclusion of aperture stops may result in the overall size of the detector being increased to an unacceptable level.

It is desirable to use a light beam in which the light is made as parallel as possible. A common method of forming a near-parallel light beam is to use a separate beam-forming lens, with the light source in the focal plane of the lens. In that case, the divergence of the light beam is fixed by the ratio of the lens' focal length to the diameter of the source. If the normal 5mm-diameter LED is used as the source, the focal length of the lens must be approximately 25mm to achieve a beam divergence of 5° each side of the beam axis. The overall length of the assembly using such a lens becomes impractical in a small detector.

An object of the preferred embodiments of the subject invention in this second aspect is to produce a narrow light beam having low divergence within a small envelope. In one aspect of the invention this can be achieved by using a small light source (preferably in the form of a LED chip device) in Surface-Mount Device (SMD) technology, in association with a high-quality lens of relatively-short focal length. The term 'SMD LED' as used hereafter is intended to include a laser diode. The term 'light source' includes a source of non-visible light, to the extent such sources are usable in smoke detectors.

In this aspect, the invention is a smoke detector that includes: a printed circuit board; a surface-mount-device (SMD) light source, preferably a light-emitting diode (LED), mounted on the printed circuit board; a light-directing means disposed over the light source and adapted to direct light emitted by the light source such that the directed light comprises a beam projected in a direction generally parallel to the surface of the printed circuit board; and, a sensor for receiving light scattered by smoke from the projected beam.

Preferably, the sensor is mounted on the printed circuit board.

Preferably, the light source is mounted on the printed circuit board to emit light in a direction generally normal to the surface of the board.

Preferably, the light-directing means includes a light-reflective surface. More preferably, the light-directing means includes a prism with a light-entry surface, the light-reflective surface and a light-exit surface, and wherein the light-reflective surface acts to both reflect and focus light.

Preferably, the light-directing means may include a prism. More preferably, the light-directing means also includes a beam-forming lens. In a first preferred arrangement, the lens is separately formed from the prism. In the first arrangement, the prism has a light-entry face, a light-reflective face, and a light-exit face, and the lens is positioned downstream of the light-exit face of the prism. In a second preferred arrangement, the lens is formed as part of the prism, and more preferably, the lens is formed in one face of the prism. In one form of such more preferable arrangement, the prism has a light-entry face, a light-reflective face, and a light-exit face, and the beam-forming lens is formed in the light-exit face. In another form of such more preferable arrangement, a laser diode is used as the SMD LED, and the beam-forming lens is formed in the light-entry face rather than the light-exit face.

Preferably, the light-directing means includes a housing with a first side having a first aperture, the first side facing the printed circuit board. More preferably, the first aperture is circular and is centred in the first side of the housing. Even more preferably, the housing also has a second side with a second aperture, the second side being a side through which the projected beam leaves the light-directing means. Yet more preferably, the second aperture is circular and is centred in the second side of the housing. Even still more preferably, the prism is positioned in the housing such that light that enters through the first aperture is directed to leave through the second aperture.

Preferably, the prism is positioned in the housing such that the light-entry face extends generally parallel to the printed circuit board, the light-exit face extends generally normal to the printed circuit board, and the light-reflective face extends at an angle to, and between outer ends of, the light-entry and light-exit faces. More preferably, the light-reflective face extends at an angle of 45° to the light-entry and light-exit faces of the prism.

Preferably, the housing has a pair of resilient legs each fitting into a respective aperture in the printed circuit board for retaining the light-directing means on the board.

Preferably, the housing has an arm portion extending in the direction of the projected beam, the arm portion having an aperture positioned directly above the light sensor on the board, the aperture in the arm portion allowing light scattered from the projected light to pass through and strike the light sensor.

To reduce further the undesirable divergence of the beam in the field of view of the sensor, preferably the beam effectively is focussed to provide an image of the light source at a point above the sensor, rather than being nominally parallel. In the latter case the image of the light source is theoretically at infinity. More preferably, the lens is positioned and sized such that a real image of a die of the LED is formed by the projected light in a first plane which extends through the arm aperture. Even more preferably, a real image of the first circular aperture is formed by the projected light in a second plane which is positioned downstream from the first plane.

This principle forms a third aspect of the invention, according to which there is provided a smoke detector comprising a light source, means for directing a beam of light from the light source across a field of view of a sensor for receiving light scattered by smoke from the projected beam, the beam directing means being configured to form a real image of the light source in the field of view of the sensor.

The sensor field of view may have an axis which intersects the beam substantially orthogonally, the beam-directing means being configured to form the real image of the light source substantially at the intersection of the beam and the axis of the sensor field of view.

The light-directing means may comprise a stop aperture, the light-directing means being configured to form a real image of the aperture downstream of the real image of the light source. Preferably, a light trap is disposed at the location of the real image of the aperture; this principle forms a further aspect of the invention. According to that aspect there is provided a smoke detector that includes a light source, means for directing a beam of light from the light source across a field of view of a sensor for receiving light scattered by smoke from the projected beam, and a light trap downstream of the sensor for receiving the projected beam. The light-directing means includes a stop aperture and is configured to form a real image of the aperture at the light trap.

Preferred features of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:-

Figure 1 is an exploded perspective view of an embodiment of the smoke detector of the invention, the view showing a base, a cover, a circuit board and components mountable on the circuit board;

Figure 2 is an exploded side view of the smoke detector of Figure 1;

Figure 3 is a schematic side view of a light source, a light beam produced by the light source, and a light sensor in the preferred embodiment of the invention;

Figure 4 is a schematic end view of the light source, light beam and light sensor of Figure 3;

Figure 5 is a schematic side view similar to Figure 3 but also illustrating a cylindrical condenser lens;

Figure 6 is a schematic end view similar to Figure 4 but also illustrating the cylindrical condenser lens;

Figure 7 illustrates the variation in photodiode response with incident angle for three positions of the photodiode;

Figure 8 illustrates the variation in photodiode response with incident angle for two sizes of photodiode;

Figure 9 is a plan view of a sensor enclosure having an aperture in which a pair of opposite edges are delta-shaped and extend toward each other; and,

Figure 10 is a schematic side view of a light sensor assembly having three light receptors offset from each other in the direction of the path of the light beam.

Figure 11 is a side view through the light-directing unit of figure 1, the view schematically illustrating, for the case where the lens is formed in the light-exit face of the prism, the path of a light beam from its emission by the Surface-Mount-Device(SMD) LED chip device on the printed circuit board to a point where the light beam passes above the light sensor on the board;

Figure 12 is the side view of Figure 11, but illustrating the positions at which real images are formed of the LED die and the first circular aperture of the light-directing unit;

Figure 13 is a side view of a second embodiment of the light-directing unit, in which the beam-forming lens is part of the unit but not formed as part of the prism;

Figure 14 is a side view of a third embodiment of the light-directing unit, in which the unit has no beam-forming lens and in which the light-reflective face of the prism directs the light;

Figure 15 is a side view of a fourth embodiment of the light-directing unit, in which a laser diode is used as the SMD LED, and a beam-forming lens is formed on the light-entry face of the prism;

Figure 16 is a side view of an embodiment of a further aspect of the invention; and,

Figure 17 is a schematic plan view of a light trap that is positioned to trap light at the plane Y in Figure 12.

As well as designing a smoke detector to maximize the amount of scattered light falling on the light sensor, it is important to also design it such that a minimum amount of stray light is able to fall on the light sensor, even when the sensor has a wide field-of-view. The stray light originates from the light beam but is not scattered directly to the sensor. Instead it is reflected once or more from the interior surfaces of the detector and reaches the sensor (much attenuated but in total still significant) only indirectly. The amount of stray light within a chamber of a smoke detector is typically defined, in terms of a relative value compared to the light-beam signal, by the parameter: 'percent of the light-beam signal at 3%/ft obscuration'. For the detector hereafter described, this parameter typically has a value of <10% of the signal, which inversely equates to a 'Normalized Figure of Merit' (NFM: another term used in the detector field) of 10. Detectors in the prior art may have a NFM of 3, meaning that the sensors in such detectors are exposed to more than three times as much stray light as in the present embodiment. Because prior art detectors have had the problem of their light sensors being exposed to stray light at levels significantly above those which the sensor of the subject detector is exposed, the design of the sensors in the prior art detectors has been oriented towards overcoming that problem. With the subject detector, the significantly-lower amount of stray light within the detector chamber can remove it as a dominating sensor design consideration, and instead allows sensor design to be concentrated on the balance between the forwardly-directed level and the rearwardly-directed level of light that is scattered from the light beam.

In recent years small-sized LEDs have become available as surface-mounted devices in Surface-Mount Device (SMD) technology. Newer SMD LED devices, such as the one used in this invention, are chip devices in which the LED die is mounted on a small insulating substrate and is over-moulded with a small beam-forming lens. The optical axis of the device is normal to the surface of the printed circuit board (PCB) on which it is mounted.

Because the SMD LED lens is very small, typically 1.8mm in diameter, a supplementary beam-forming lens with a focal length of only 8mm will give a beam of the required diameter and divergence. The overall assembly is therefore only one third of the size that is possible using a 5mm-diameter LED. The fact that the LED can be placed by machine is also a great advantage when compared with through-hole devices that must be fitted manually.

The smoke detector of the first embodiment, shown in Figures 1 and 2, has a base 20, a cover 22 that fits on the base 20, and a circuit board 24 fitted between the base 20 and the cover 22. On the circuit board 24 is fitted a compact light source, for example SMD LED chip package 26. A light sensor is generally designated as 30, and a pair of holes 32 each extend on an opposite side of a line drawn between the light source 26 and the light sensor 30.

The smoke detector further includes a prism carrier 34 which includes a carrier base 36, a prism 38 mounted in the carrier base 36, and a carrier cover 40 mounted on the carrier base 36 to hold the prism 38 on the carrier base 36. The prism carrier 34 is made of moulded plastic and has an integral pair of legs 42 each having a hooked end 44 extending through a respective hole 32 in the circuit board 24 and flexibly engaging with an underside of that board so as to secure the prism carrier 34 to the board 24. One part of the prism carrier 34 is formed as an arm 46 that extends above the light sensor 30. The arm 46 has an aperture 48 in its base to allow light scattered from the redirected light beam to pass through to the light sensor 30.

A disadvantage with the SMD LED chip package 26 is that the light beam it creates extends normal to the PCB 24, whereas the beam ideally should be parallel to the surface so that a low profile can be achieved for the detector. To achieve this, the prism 38 is fitted above the LED chip package 26 to redirect the beam through 90°. The 90° beam redirection is achieved through use of a 45° light-reflective back face on the prism 38. Preferably, the prism 38 is moulded from a clear plastic material, and a beam-forming lens 150 is formed on its light-exit face 152. The prism 38 also has a planar light-entry face 154 adapted to face toward the LED chip package 26. The 45° light-reflective face 156 connects to the outer ends of the light-entry face 154 and the light-exit face 152. The dimensions of the light-entry face 54 and the light-exit face 152, and the focal length of the beam-forming lens 150, are calculated so as to produce a light beam that is parallel or near-parallel to the surface of PCB 24.

As described here, the optical axis of the sensor intersects the axis of the light beam orthogonally. This is the preferred arrangement, but in principle the axis of the sensor could be offset so as not to intersect the axis of the beam, but to lie in a plane orthogonal to it. Alternatively or in addition the axis of the sensor could intersect the beam axis obliquely (i.e non-orthogonally) or may lie in a plane which to which the beam axis is not orthogonal. What is required is that the field of view of the sensor intercepts the light beam. Non-orthogonal or offset cases may find application where specific sensing effects are required; their performance may be more difficult to predict than the orthogonal intersection case, but can be established empirically by routine experiment.

The light source in Figures 3 to 6 is generally shown as the box 50. Although the box 50 may represent a LED whose light is turned 90° by a lens to form a light beam 52, such as in the arrangement shown in Figures 1 and 2, the box 50 may also represent a LED or other light source that is oriented so as to directly transmit its output as the light beam 52. The light beam 52 is of small diameter and low divergence, such that very little light strays outside the main envelope of the beam. The light sensor 30 has a light-receiving surface 56 enclosed within an enclosure 58. The light-receiving surface 56 is a sensitive surface of a plane silicon Positive-Intrinsic-Negative (PIN) photodiode that has an approximately-Lambertian variation of sensitivity with angle of incidence. The surface 56 is planar, though a surface with slight curvature might also be used. The planar surface 56 extends generally parallel to the axis 60 of the light beam 52. The enclosure 58 has a rear edge 62 and a front edge 64 that, together with side edges 66 and 68 (see Figure 4) define an aperture 70 of the light sensor 30.

The aperture 70 is sized to restrict the angles over which the light sensor 30 receives light scattered from the light beam 52. The position of the rear edge 62 of the aperture 70 determines the field-of-view for forward-scattered light; forward-scattered light incident on the surface at any greater angle of incidence than 'A' is prevented from reaching the light-receiving surface 56. Similarly, the position of the front edge 64 of the aperture 70 determines the field-of-view for backward-scattered light; backward-scattered light incident at any greater angle than 'B' is prevented from reaching the light-receiving surface 56. The value of the two fields-of-view can be set independently of each other by the positioning of the rear edge 62 and the front edge 64 of the enclosure 58, and this provides a means for the smoke detector to achieve a balance of sensitivity to both pale smoke and dark smoke.

As shown in Figure 4, the position of the side edges 66 and 68 of the aperture 70, forming an angle 'C' with the respective side edges of the light-receiving surface 56, determine the lateral field-of-view for both the forward-scattered light and the backward-scattered light. The lateral field-of-view extends just outside the side boundaries of the light beam 52 so as to exclude, as far as possible, any light scattered outside the light beam 52 or any stray reflected light from reaching the light-receiving surface 56.

The light sensor 30 is mounted on the circuit board 24. The chamber formed by placing the cover 22 on the base 20 of the smoke detector houses the circuit board 24 and has dark walls to reduce the possibility of reflected light from the light source 50 reaching the light sensor 30. The cover 22 and base 20 each has perforations and baffles arranged on its periphery such that external light is unable to enter the chamber they form when connected, but smoke carried by the outside air is able to easily enter the chamber.

In this preferred embodiment, the diameter of light beam 52 is 3mm, and the upper face of the enclosure 58 is situated approximately 3mm from the longitudinal axis of the light beam 52. This separation distance ensures that small insects walking across the upper face of the enclosure 58 will not enter the path of the light beam 52 to cause light scattering that will trigger a false alarm.

The distance between the light-receiving surface 56 and the aperture 70 is made as small as possible so as to achieve the field-of-view values discussed above. In this embodiment, the light-receiving surface 56 is positioned approximately 3mm below the aperture 70. Thus the light-receiving surface 56 of light sensor 30 is situated only approximately 6mm from the longitudinal axis of the light beam 52. Such close spacing increases the amount of scattered light received by the light-receiving surface 56, and also allows for a compact smoke-detector design.

Although the light-receiving surface 56 is ideally a sensitive planar surface of a plane silicon PIN photodiode, that surface could have a curvature; however, a curved surface would have a degraded performance in comparison to the planar surface. The area of the light-receiving surface in the preferred embodiment is $7mm^2$. The light sensor 58 may be implemented in Surface-Mounted Device (SMD) technology by mounting the plane silicon PIN photodiode on the circuit board 24.

Figures 5 and 6 illustrate the same arrangement as in Figures 3 and 4, but with a cylindrical condenser lens 72 added to improve the amount of light collected by the light-receiving surface 56. The axis of the cylindrical surface of the lens 72 extends parallel to light beam 52. Since the angular field-of-view can be very limited in the plane normal to the light beam 52, a useful increase in collected light is achieved by using the lens 72. In Figure 6, the presence of the lens 72 allows the width of the aperture to be increased without increasing the angle 'C'. The spacing between the side edges 66 and 68 of the enclosure 58 in Figure 6 could be increased over the spacing between those edges shown in Figure 4. It should be appreciated that, although the side edges 66 and 68 in Figure 4 are depicted as being in the same plane as the edges 62 and 64 in Figure 3, the benefits of the invention could still be obtained if those pairs of opposed edges were in different planes.

Figure 7 schematically illustrates the response of the light-receiving surface 56 (photodiode) of Figure 3 as a function of position of the rear edge 62 and front edge 64 of the enclosure 58. As would be expected from considering Figure 3, the response of the light-receiving surface 56 is zero for backward-scattered light that has an angle of incidence greater than B as well as for forward-scattered light that has an scatter angle of incidence greater than A. Figure 7 illustrates how the photodiode response varies between the A and B extremes. The response is determined by the relative sizes and positions of the sensor aperture and the sensitive area of the photodiode. In the preferred embodiment of Figure 3, the dimension of the light-receiving surface 56 in the direction of the light beam axis is only slightly smaller than the aperture dimension, i.e. the distance between the edges 62 and 64. The light-receiving surface is approximately central in the aperture, giving a variation of sensitivity with angle as shown by the line (i) on Figure 7. If, instead of being centrally positioned, the surface 56 is moved to the right, i.e. in the same direction as the light beam, the response becomes biased toward the forward-scattered light, as shown by the line (ii). Alternatively, if the surface 56 is moved leftward from the central position, the response becomes biased toward the backward-scattered light, as shown by the line (iii). A detector having a variation with angle as shown by the line (iii) will have a better response to dark smoke than will a detector having a response shown by the line (ii), which will have a better response to pale smoke.

Investigations have also been made on the effects of sensor area, field-of-view and related parameters. In particular, an investigation has been made of the effect of using a photodiode whose dimensions are small compared with those of the accompanying aperture. If photodiode dimensions are reduced while the other dimensions remain fixed, the sensitivity as a function of angle that was depicted in Figure 7 shows a much more rapid cut-off, since the light-receiving surface of the photodiode approximates to a point receiver. The variation of sensitivity with incident angle then varies as shown by the line (iv) in Figure 8. This sharp cut-off makes it more difficult to balance the effects of the high-intensity forward scatter with the much lower-intensity right-angle scatter.

Such rapid cut-off can be made more gradual if the light shields are not straight edges placed normal to the light beam. Since the light beam has a finite diameter, it is possible to shield different regions to differing extents. For example, using the butterfly-shaped sensor aperture 80 (having a pair of delta-shaped opposite edges), as shown in Figure 9 superimposed on the standard straight-edged sensor aperture 82 earlier discussed, the incident angle for scatter of light from rays near the center of the light beam will be limited to values near 0°. Rays at the edge of the beam will, on the other hand, contribute over a wider angular range, thereby making the overall variation with angle more gradual. In Figure 9, the light-receiving surface is designated 84.

Another investigation concerns the effects of using a light sensor having multiple light-receiving surfaces, i.e. multiple photodiodes, as illustrated in Figure 10. The use of multiple light receptors is simplified by using the sensor aperture geometries previously described. In fact, this embodiment has similarities with the Figure 7 embodiment. If two or more small-area light receptors are arranged below the sensor aperture, spaced along a line parallel to the axis of the light beam, each light receptor will respond to a different range of scatter angles. As before, the angular response of each receptor can be tailored by its position relative to the edges of the aperture. The multiple receptors may be discrete photodiodes, or may be multiple photodiodes within the same package in the form of a linear array. Although the fields-of-view of the three photodiodes 90, 92 and 94 in Figure 10 overlap, photodiode 94 will receive predominantly forward-scattered light while photodiode 90 will receive predominantly backward-scattered light.

Although the arrangement described with reference to figures 1 and 2 is an improvement on previous systems that use 5-mm LEDs, the amount of light energy extending outside the main light beam envelope is still quite high. This is because the LED chip package 26 allows light to escape in all directions, thereby expanding the nominal small source size. Referring to figure 11, the stray light is partially removed by the placement of a first circular aperture 160 in a bottom first side 162 of the carrier base 36, the first side 162 extending between the LED chip package 26 and the prism light-entry face 154. The first circular aperture 60 blocks all light rays except those extending close to the optical axis of the LED chip package 26. A second circular aperture 164 is formed in the carrier cover 40 so as to sit in front of beam-forming lens 150 when the carrier cover 40 is mounted on the carrier base 36 with the prism 38 sitting therebetween; the second circular aperture 164 blocks any off-axis light rays that emerge from the beam-forming lens 150. The carrier cover 40 has front and back brackets 166 that are captured by respective detents (not shown) within the carrier base 36 to hold the cover 40 on the base 36.

In the side view of Figure 11, a light beam is emitted upward from the SMD LED 26. A portion of that light beam passes upward through the first circular aperture 160 of the prism carrier 34; any stray light in side lobes of the light beam are there blocked. The light beam is diverging as it enters the light-entry face 154 of the prism 38, and is still diverging as it is reflected by the light-reflective face 56 and moves toward the light-exit face 152. A circular central portion of light-exit face 152 is formed as the beam-forming lens 150, and the light beam is caused to converge by its passage through the lens 150. Only a portion of such converging light beam passes through the second circular aperture 164 of prism carrier 34; any off-axis light rays that emerge from the lens 150 are thereby removed. The resulting converging light beam extends above the arm 46 of prism carrier 34, and crosses above the aperture 48 which sits directly above the light sensor 30. In operation of the smoke detector, light scattered from the light beam and passing above the aperture 48 is detectable by the light sensor 30. The field of view of the sensor, the principal axis of which is shown at 31, is directed orthogonally of the light beam.

As shown in Figure 12, the focal length of the beam-forming lens 150 is calculated such that a die 168 of the LED 26 is imaged in a plane X extending through the aperture 48 in the arm 46, aligned with the axis 31 of the sensor field of view. By imaging the die 168 in the region above the sensor, the effective diameter of the beam in this region is minimized. This makes the detector less susceptible to false alarms from small insects or other foreign bodies that may find their way onto the top face of arm 46, within the field-of-view of the sensor 30. The first aperture 160 is imaged in a plane Y which is further downstream and at a convenient distance from the front face of the beam-forming lens 150. The position of the image in plane Y is independent of the position of the output face of the LED chip package 26, and is fixed by the relative positioning of the first aperture 160 and the lens 150. The plane Y is the location of a 'light trap' (or 'dump') designed to absorb all or almost all of the energy in the beam. The light trap in this smoke detector is an L-shaped chamber 120 (shown in schematic plan view in Figure 17), having a first passage 122 meeting, at an angle of about 45°, a second shorter passage 124 with a closed outer end 126. The chamber shape is such that entering light is reflected multiple times within the chamber, with only a small amount of the light able to escape from the chamber. The provision of such a light trap is greatly simplified when the exact location of the beam is known, and stray reflections can be eliminated. It is therefore important that the prism carrier 34 is assembled very precisely so that the beam position is always known within close limits.

By focussing the beam to provide an image of the LED in plane X, the highest-intensity part of the beam is convergent to the plane of the image, and thus is most concentrated at this point. Unwanted divergence thus is reduced.

A second embodiment of the subject invention utilizes the alternate prism carrier 170 shown in Figure 13. The prism carrier 170 operates in a similar way to prism carrier 34 of Figure 11 except that the beam-forming lens 150 on the light-exit face 152 of the prism 38 has been replaced by a separate beam-forming lens 172. The lens 172 is mounted in the prism carrier 170 so as to be just forward of a planar light-exit face 174 of prism 176. Other parts of the prism carrier 170 remain the same as in the prism carrier 34. As with the lens 150 of the first embodiment, the position and focal length of lens 172 are such that the real images X and Y shown in Figure 12 are formed. A real image of the lens die 177 is formed in a first plane extending through arm aperture 178, and a real image of the first circular aperture 180 is formed in a second plane (not shown) downstream of the first plane.

An advantage of the first and second embodiments of the light source is that a portion of the distance (focal length) between the lens and the LED is in the horizontal axis, allowing a reduction in the height of the prism carrier.

A third embodiment of the light source utilizes the alternate prism carrier 190 shown in Figure 14. In this embodiment, the light-reflective face 192 of the prism 194 has a central section 196 that acts to both reflect the light and change its focus, i.e. a beam-forming lens is not required. Thus a diverging light beam from the LED 198 not only has its direction changed by the light-reflective face 192 but is also refocused into a converging beam with images at planes X and Y as in figure 12.

A fourth embodiment of the subject invention utilizes a prism carrier 100 as shown in Figure 15. In this fourth embodiment, a laser diode 102 is used as the SMD LED; such laser diode may be, for instance, a VCSEL laser device. The use of a laser diode, with a reduced emitting area compared to a non-laser diode, as the light source allows for the beam-forming lens to be placed closer to the light source than was possible with the other embodiments while still achieving a small beam divergence. The beam-forming lens may be formed on the light-entry surface of the prism. In Figure 15, the beam-forming lens is shown as a bump 104 on the light-entry surface 106 of the prism 108. If a VCSEL or other type of laser diode is used as the source, there is still an advantage to forming an image of the emitting area in the region over the sensor. There is certainly an advantage in imaging the first aperture in the plane of the light trap in that the position of the light source thereby becomes less critical. Also, even with a laser diode there exists stray, off-axis light, but the effect of that off-axis light can be minimized using the lens and the arrangement of stops.

In Figure 16 the light source is provided by a sideways-looking through-hole LED 110 mounted on the PCB 24. This source has a LED die 112 and emits a beam of light sideways and parallel to the PCB 24 through an integral lens 114 and stop aperture 116, and thence through beam-forming lens 50 and circular aperture 164 as already described with reference to Figures 11 and 12. The lens 150 produces real images of die 112 and aperture 116 at planes X and Y respectively as already described with reference to Figures 11 and 12. Parts corresponding to those of Figures 11 and 12 carry the same reference numerals in Figure 16.

The embodiment of Figure 16 thus provides the beam-concentrating advantages of imaging the light source at plane X, on the axis of the field of view of sensor 30, without the need for a prism or other device to turn the light beam through 90° from a SMD LED on the PCB 24. However, the use of a through-hole LED may increase assembly costs. The narrow beam and compactness of a SMD LED can still be obtained if the through-hole LED 110 is replaced by a SMD LED on a small PCB set orthogonally to the board 24. However, there will be again a penalty in greater complexity and assembly costs; thus the arrangement of Figures 1, 2 and 11 to 15 is generally to be preferred.

While the present invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than limitation, and that changes may be made to the invention without departing from its scope as defined by the appended claims.

Each feature disclosed in this specification (which term includes the claims) and/or shown in the drawings may be incorporated in the invention independently of other disclosed and/or illustrated features.

To summarise the preferred embodiments of the first aspect of the invention, a smoke detector has a light sensor positioned such that a light-receiving surface of the sensor extends generally parallel to a light beam generated by a light source of the smoke detector. The light sensor has an enclosure surrounding the light-receiving surface, which enclosure has an aperture in a side facing the light beam. The front and rear edges of the aperture (with reference to the direction of the light beam), as well as the two side edges extending normal to the front and rear edges, are positioned so as to affect the amount of scattered light from the light beam that reaches the light-receiving surface. In particular, the position of the front and rear edges of the aperture can be used to create a balance of sensitivity to forward-scattered pale-coloured smoke and backward-scattered dark-coloured smoke. The light-receiving surface may be a light-sensitive surface of a plane silicon PIN photodiode.

To summarise the preferred embodiments of the second aspect of the invention, a scattered-light smoke detector with compact light source includes a surface-mount-device (SMD) light-emitting diode (LED) mounted on a printed circuit board, and a light-directing unit mounted on a surface of the board so as to sit over the LED. The light-directing unit is adapted to direct light emitted from the LED such that a central axis of the directed light extends in a direction generally parallel to the surface of the printed circuit board. The directed light extends above a sensing surface of a light sensor mounted on the board. The light-directing unit may include a prism and a beam-forming lens, with the lens being formed in a light-exit face of the prism. Alternatively, the beam-forming lens may be separate from the prism, and positioned downstream of the light-exit face of the prism. Another alternative is to have a light-reflective face of the prism perform the function of the beam-forming lens, so that no separate lens is required. The use of a SMD LED in association with a proximate means for redirecting and refocusing light allows for construction of a compact low-profile smoke detector.

CLAIMS:

1. A smoke detector having a light sensor, the light sensor being positioned such that its optical axis extends transversely of (and preferably generally perpendicular to) a light beam generated by a light source of the smoke detector, the sensor having a pair of light shields positioned between the light beam and the light-receiving surface for defining the directions from which scattered light from smoke particles in the light beam can strike the light-receiving surface, the position of the shields being chosen in accordance with a desired ratio of forward-scattered light striking the light-receiving surface to backward-scattered light striking that surface.

2. The smoke detector of claim 1, wherein the first and second light shields are formed as a first pair of opposed edges of an aperture, the aperture being positioned between the light beam and the light-receiving surface, light scattered from smoke in the light beam passing to the light-receiving surface through the aperture.

3. The smoke detector of claim 1 or 2, wherein the light shields are positioned relative to the light-receiving surface such that light scattered from the light beam strikes the light-receiving surface at an angle of incidence of 45° or less.

4. The smoke detector of claim 1, 2 or 3, wherein the light shields are positioned relative to the light-receiving surface such that maximum angle of incidence at which the backward-scattered light strikes the light-receiving surface is greater than the maximum angle of incidence that at which the forward-scattered light strikes that surface.

5. The smoke detector of any of claims 1 to 4, wherein a said light shield has an operative edge that extends generally normal to the axis of the light beam.

6. The smoke detector of any of claims 1 to 4, wherein said light shields have a pair of opposed operative edges that are, at least in part, not parallel to each other.

7. The smoke detector of claim 6, wherein the opposed edges diverge from each other with distance from the axis of the light beam.

8. The smoke detector of any preceding claim, wherein the detector has a pair of second light shields extending generally parallel to the axis of the light beam.

9. The smoke detector of claim 8, wherein each of said second light shields has an edge which is approximately on a line extending between a respective side boundary of the light beam and a respective corresponding side edge of

the light-receiving surface.

10. The smoke detector of any of claims 2 to 9, wherein the aperture is defined by a frame formed as part of an enclosure surrounding the light-receiving surface.

11. The smoke detector of any preceding claim, wherein there are a plurality of light-receiving surfaces each having a respective field-of-view defined by the light shields.

12. The smoke detector of claim 11, wherein the plurality of light-receiving surfaces are distributed parallel to the axis of the light beam.

13. The smoke detector of any preceding claim, wherein the or each light-receiving surface is a photodiode.

14. The smoke detector of claim 11, 12 or 13, wherein the plurality of light-receiving surfaces are formed by discrete photodiodes.

15. The smoke detector of claim 11, 12 or 13, wherein the plurality of light-receiving surfaces are formed by photodiodes within the same package in the form of a linear array.

16. The smoke detector of claim 13, 14 or 15, wherein

each photodiode is a silicon Positive-Intrinsic-Negative (PIN) photodiode.

17. The smoke detector of any preceding claim, wherein the light shields are spaced approximately 3mm from the longitudinal axis of the light beam.

18. The smoke detector of any preceding claim, wherein the light-receiving surface is spaced 10mm or less from the axis of the light beam.

19. The smoke detector of any preceding claim, wherein the light-receiving surface is spaced 8mm or less from the axis of the light beam.

20. The smoke detector of any preceding claim, wherein the light-receiving surface is spaced 6mm or less from the axis of the light beam.

21. The smoke detector of any preceding claim, wherein the smoke detector has a base, a cover for covering the base, and a circuit board carrying the light source, and wherein, when the cover is covering the base, the base and cover together define an internal chamber adapted to house the circuit board and to receive smoke but to block external light.

22. The smoke detector of claim 21, wherein a background light level in the internal chamber is less than 10% of a signal of the light beam at 3%/ft obscuration.

23. The smoke detector of any preceding claim, and also comprising a cylindrical condenser lens positioned between the light beam and the light-receiving surface, the axis of a cylindrical surface of the lens extending parallel to the axis of the light beam.

24. A smoke detector comprising:

a printed circuit board;

a surface-mount-device (SMD) light source mounted on the printed circuit board;

a light-directing means disposed over the light source and adapted to direct light emitted by the light source such that the directed light comprises a beam projected in a direction generally parallel to the surface of the printed circuit board; and,

a sensor for receiving light scattered by smoke from the projected beam.

25. The smoke detector of claim 24, wherein the sensor is mounted on the printed circuit board.

26. The smoke detector of claim 24, wherein the light source is mounted on the printed circuit board to emit light in a direction generally normal to the surface of the board.

27. The smoke detector of claim 24, 25 or 26, wherein the light-directing means includes a light-reflective surface.

28. The smoke detector of claim 24, 25 or 26, wherein the light-directing means includes a prism.

29. The smoke detector of claim 28, wherein the light-directing means also includes a beam-forming lens.

30. The smoke detector of claim 29, wherein the lens is formed as part of the prism.

31. The smoke detector of claim 30, wherein the lens is formed in one face of the prism.

32. The smoke detector of claim 27, wherein the light-directing means includes a prism with a light-entry surface, the light-reflective surface and a light-exit surface, and wherein the light-reflective surface acts to both reflect and focus light.

33. The smoke detector of claim 29, wherein the prism has a light-entry face, a light-reflective face, and a light-exit face, and wherein the lens is positioned downstream of the light-exit face of the prism.

34. The smoke detector of claim 31, wherein the prism

has a light-entry face, a light-reflective face, and a light-exit face, and wherein the lens is formed in the light-exit face.

35. The smoke detector of claim 31, wherein the prism has a light-entry face, a light-reflective face, and a light-exit face, wherein the lens is formed in the light-entry face, and wherein the SMD lght source is a laser diode.

36. The smoke detector of any one of claims 32 and 35, wherein the light-directing means includes a housing with a first side having a first aperture, the first side facing the printed circuit board.

37. The smoke detector of claim 36, wherein the first aperture is circular and is centred in the first side of the housing.

38. The smoke detector of claim 36 or 37, wherein the housing also has a second side with a second aperture, the second side being a side through which the projected beam leaves the light-directing means.

39. The smoke detector of claim 38, wherein the second aperture is circular and is centred in the second side of the housing.

40. The smoke detector of claim 38 or 39, wherein the prism is positioned in the housing such that light that enters through the first aperture is directed to leave through the second aperture.

41, The smoke detector of claim 36, wherein the prism is positioned in the housing such that the light-entry face extends generally parallel to the printed circuit board, the light-exit face extends generally normal to the printed circuit board, and the light-reflective face extends at an angle to, and between outer ends of, the light-entry and light-exit faces.

42. The smoke detector of claim 41, wherein the light-reflective face extends at an angle of 45° to the light-entry and light-exit faces of the prism.

43. The smoke detector of any one of claims 30 to 42, wherein the housing has an arm portion extending in the direction of the projected beam, the arm portion having an aperture positioned directly above the light sensor on the board, the aperture in the arm portion allowing light scattered from the projected light to pass through and strike the light sensor.

44. The smoke detector of any one of claims 36 to 43, wherein the housing has a pair of resilient legs each fitting into a respective aperture in the printed circuit

board for retaining the light-directing means on the board.

45. The smoke detector of any of claims 24 to 44, wherein the light-directing means is configured to form a real image of the light source in the field of view of the sensor.

46. The smoke detector of any of claims 24 to 45, wherein the sensor is positioned with an axis of its field of view directed so as to intersect the projected beam substantially orthogonally.

47. The smoke detector of claims 45 and 46, wherein the light-directing means is such as to form the real image of the light source substantially at the intersection of the projected beam and the axis of the sensor field of view.

48. The smoke detector of claim 36 and 45, wherein a real image of the first circular aperture is formed by the projected light at a position which is downstream from the image of the light source.

49. A smoke detector comprising a light-source, means for directing a beam of light from the light source across a field of view of a sensor for receiving light scattered by smoke from the projected beam, the beam directing means being configured to form a real image of the light source in the field of view of the sensor.

50. The smoke detector of claim 47 or 49, wherein the sensor field of view has an axis which intersects the beam substantially orthogonally; the beam-directing means being configured to form the real image of the light source substantially at the intersection of the beam and the axis of the sensor field of view.

51. The smoke detector of claim 49 or 50, wherein the light-directing means comprises a stop aperture, the light-directing means being configured to form a real image of the aperture downstream of the real image of the light source.

52. A smoke detector comprising a light-source, means for directing a beam of light from the light source across a field of view of a sensor for receiving light scattered by smoke from the projected beam, and a light trap downstream of the sensor for receiving the projected beam, the light-directing means comprising a stop aperture and being configured to form a real image of the aperture at the light trap.

53. The smoke detector of any of claims 242 to 52, wherein the light source is a LED.

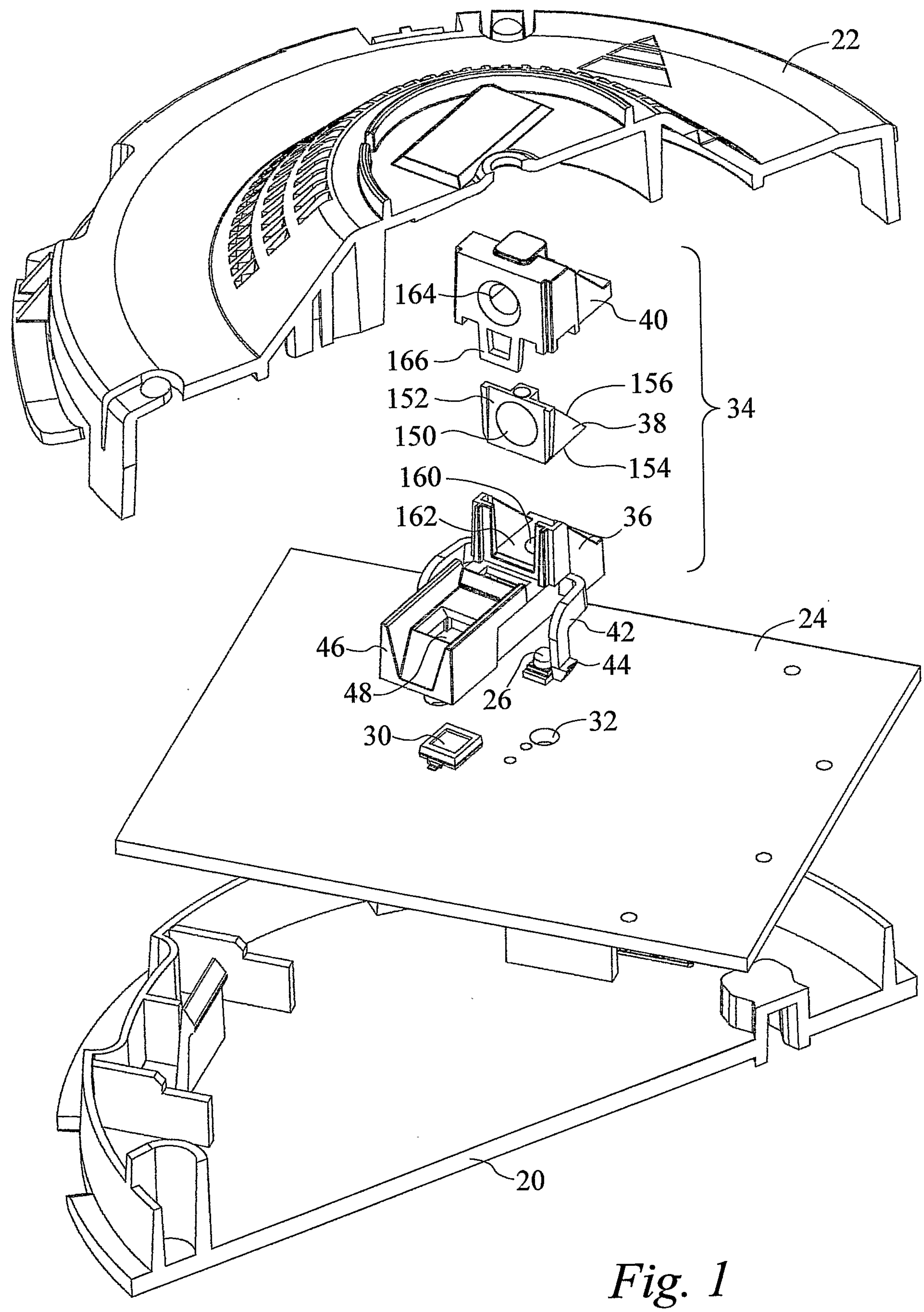
22
164
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Fig. 1

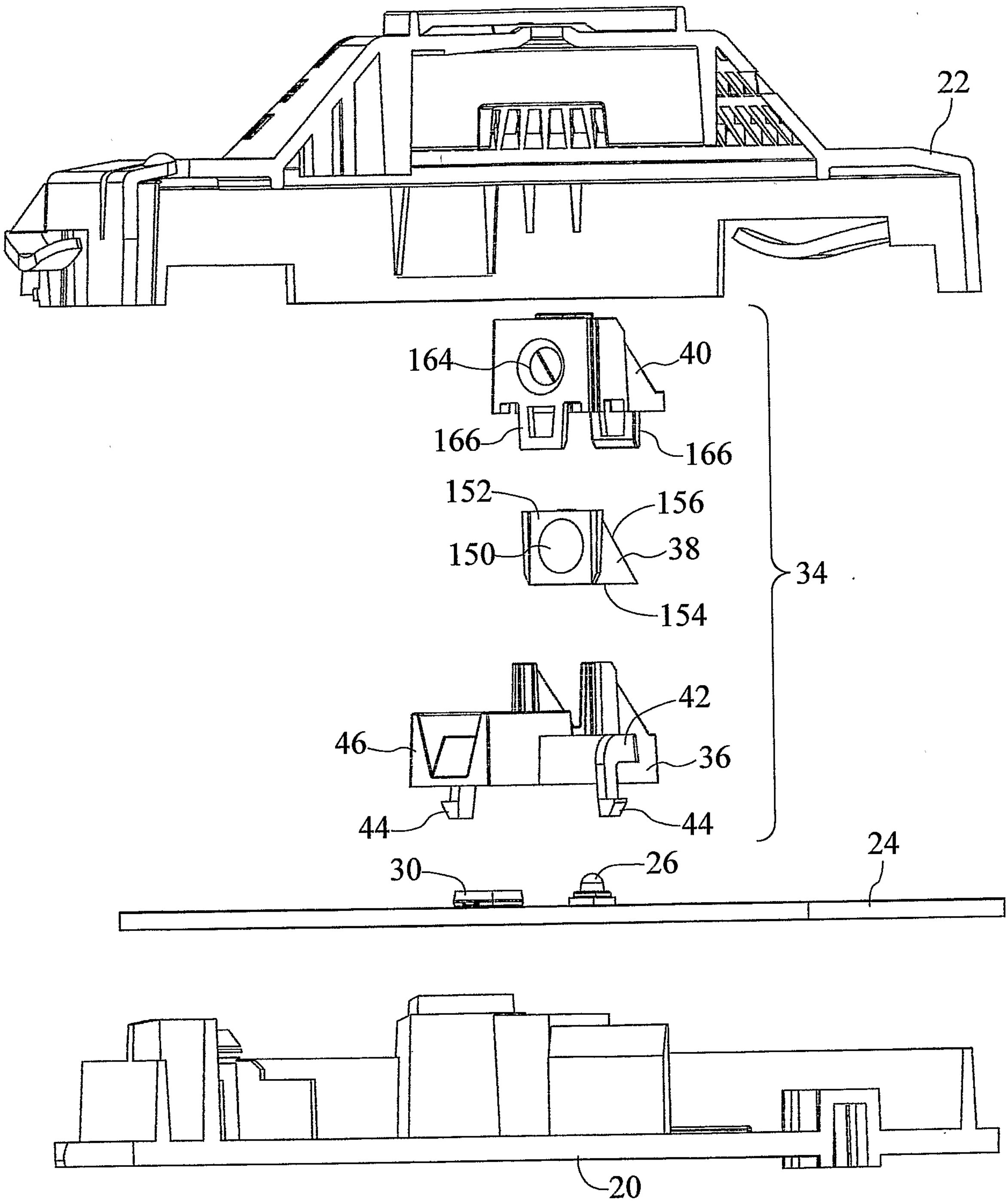

Fig. 2

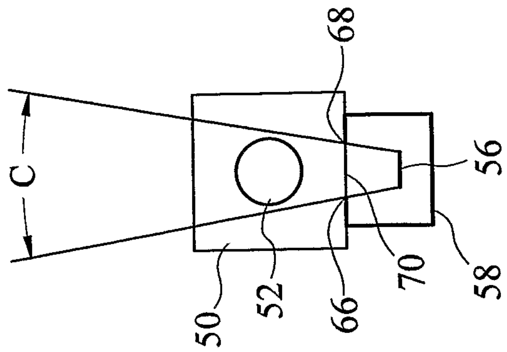

Fig. 4

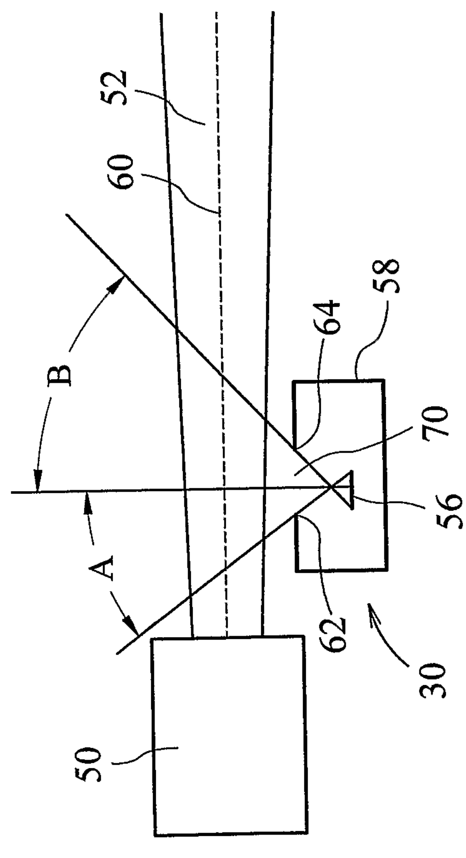

Fig. 3

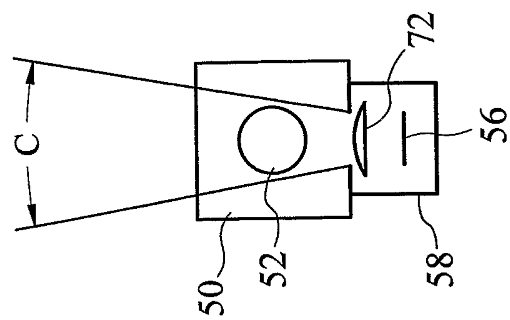

Fig. 6

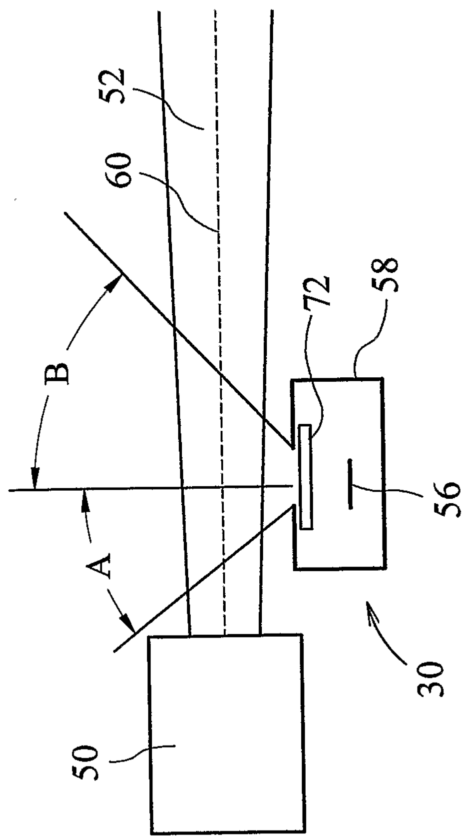

Fig. 5

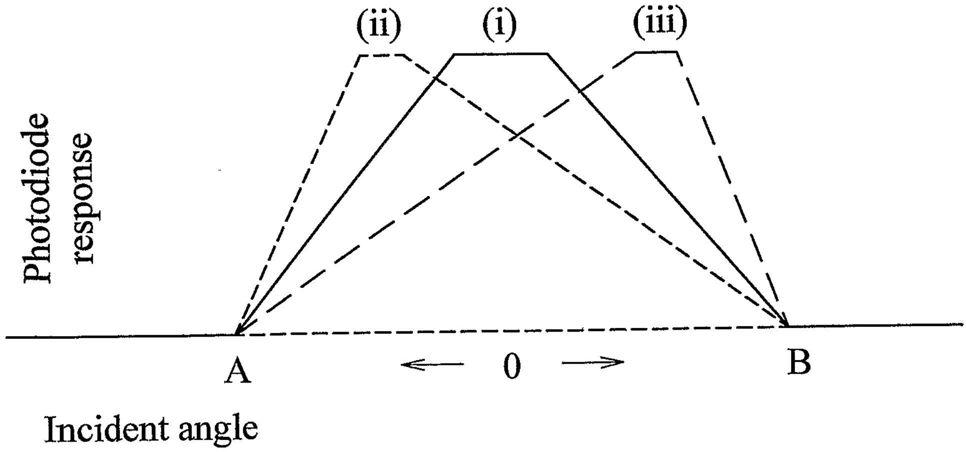
(ii)
(i)
(iii)
Photodiode response
A
0
B
Incident angle

Fig. 7

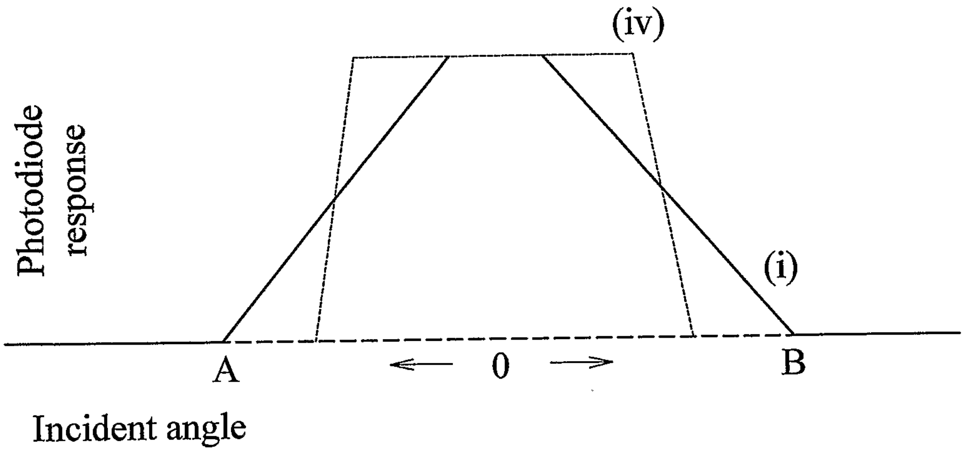
(iv)
Photodiode response
(i)
A
0
B
Incident angle

Fig. 8

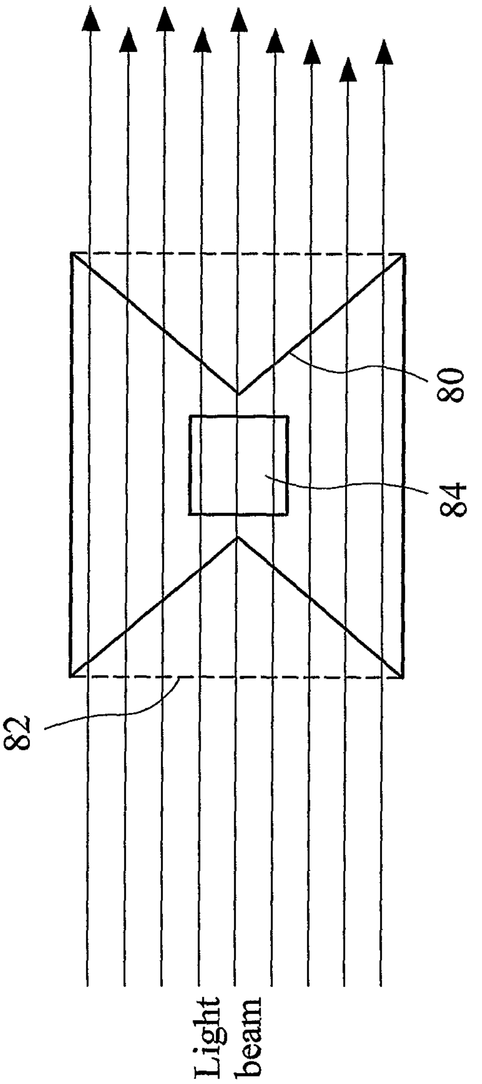

Fig. 9

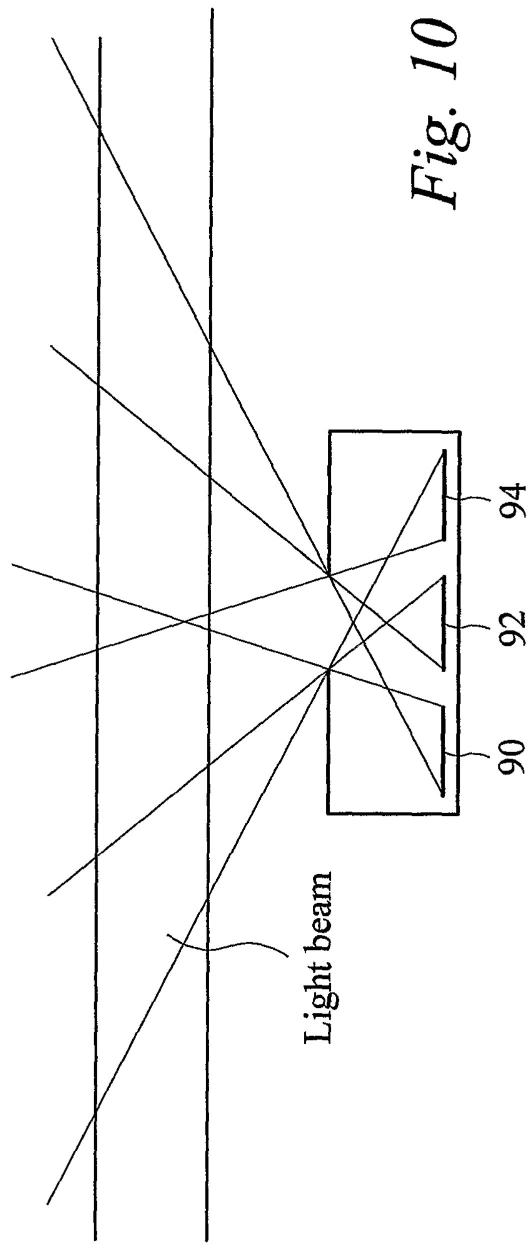

Fig. 10

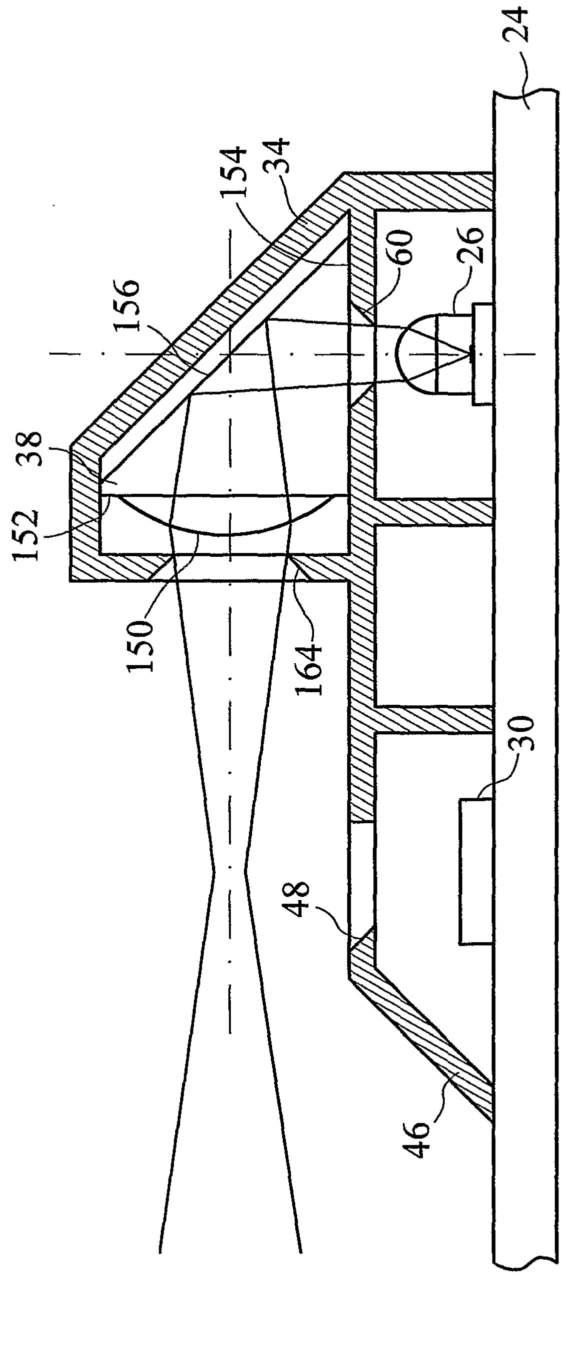

Fig. 11

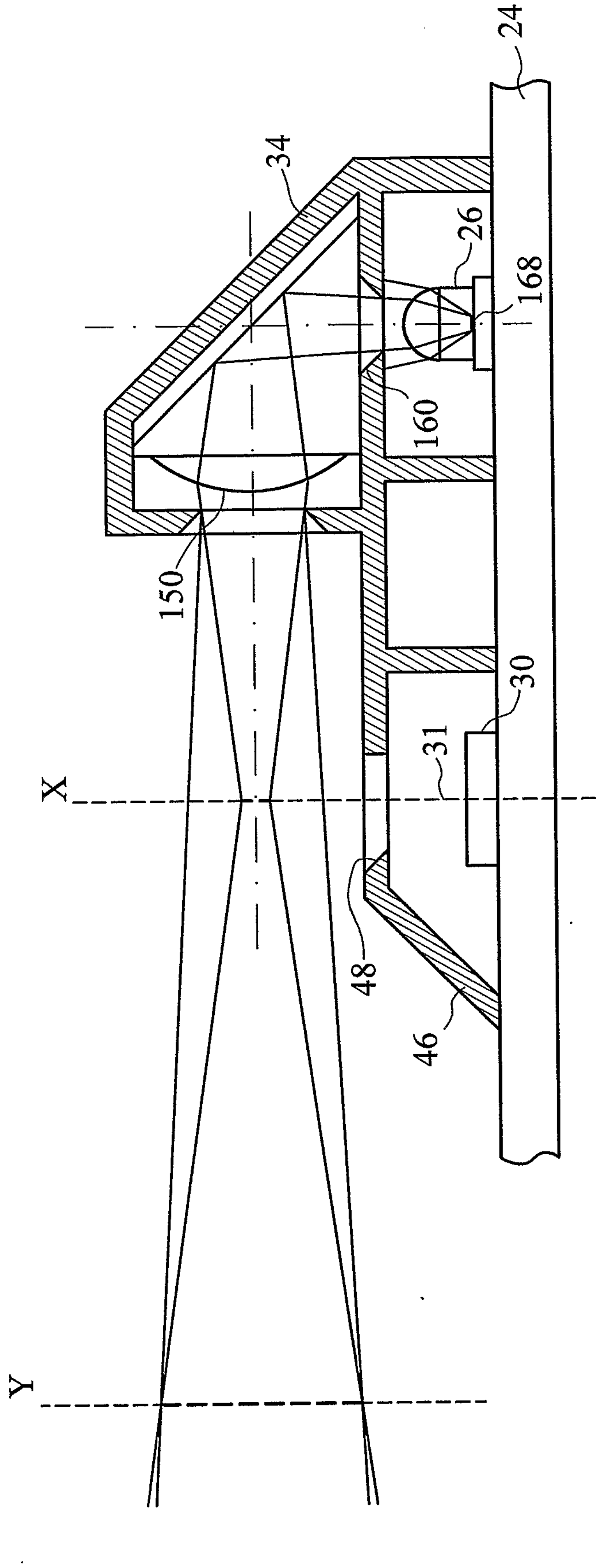

Fig. 12

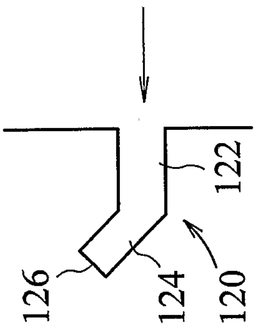

Fig. 17

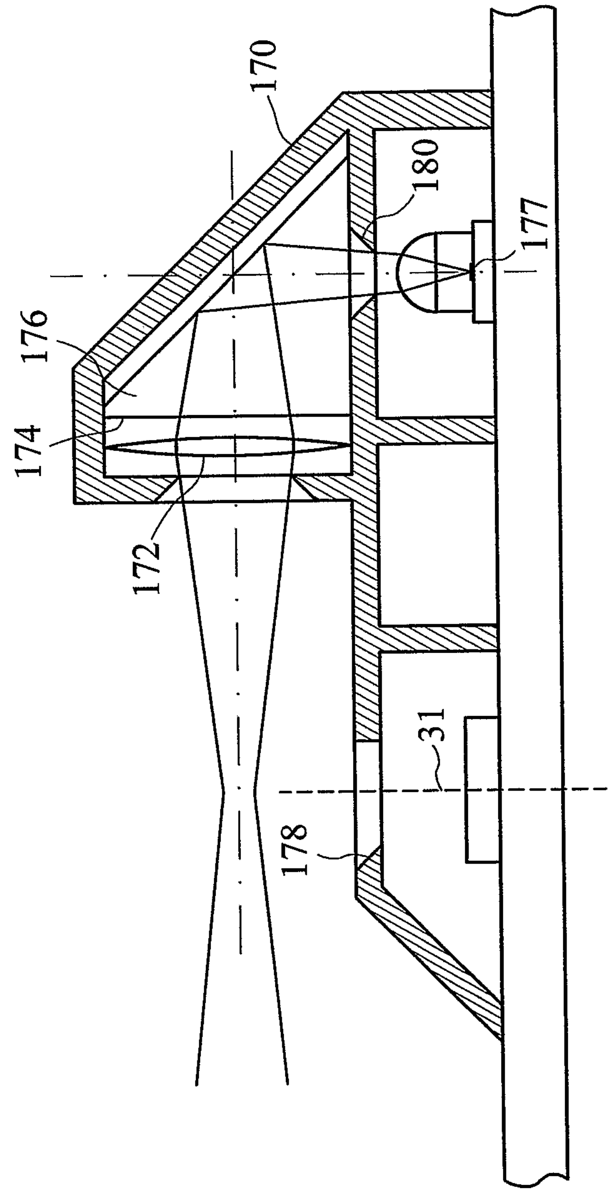

Fig. 13

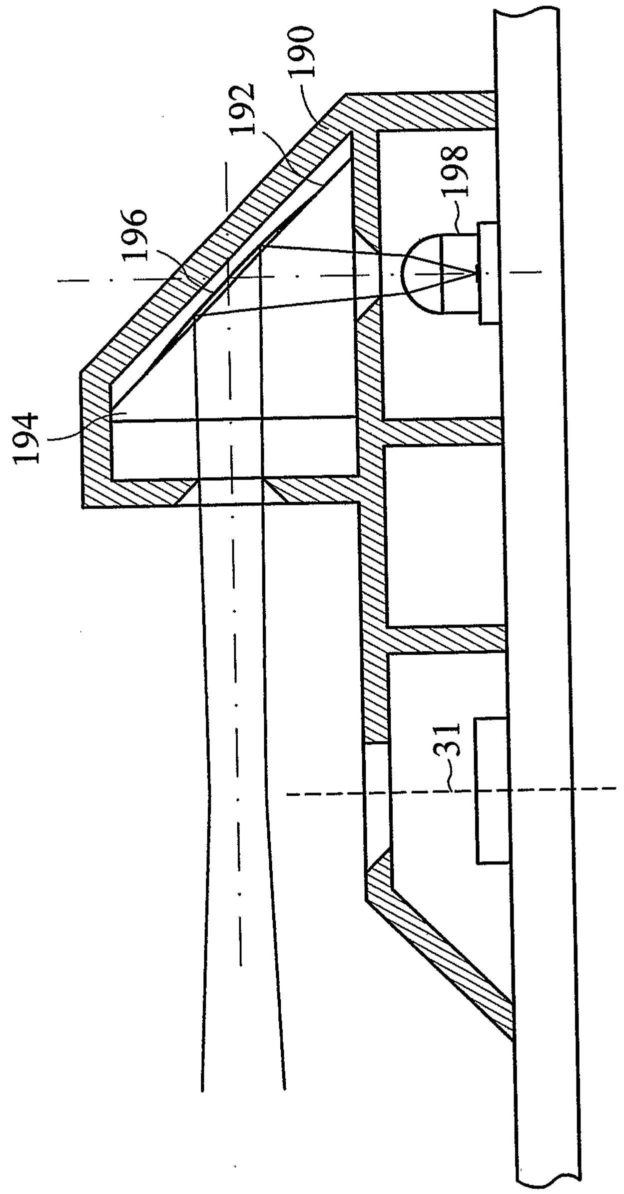

Fig. 14

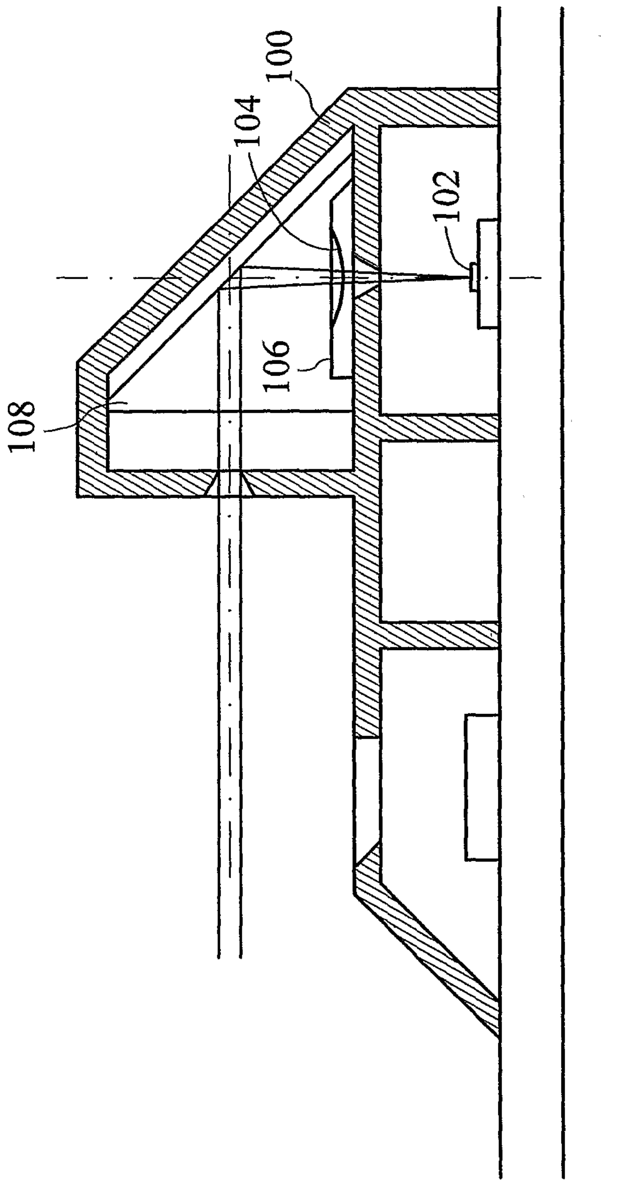

Fig. 15

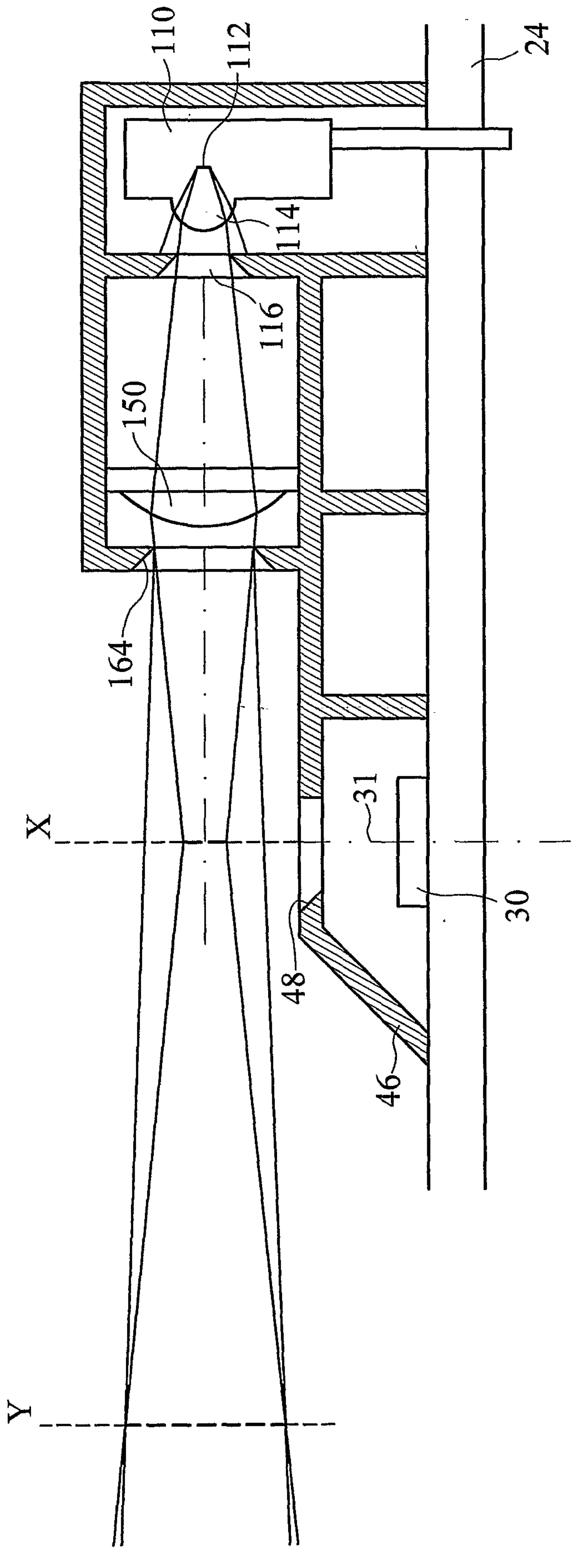

Fig. 16