Fire Research Note No. 824

A LASER BEAM FIRE DETECTION SYSTEM

by

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SUMMARY

Details of a fire detection system using the deflection of a laser beam above a fire are described. It is shown that such a system will decrease in sensitivity with the height of the compartment to be protected at a lower rate than with point detection systems. Devices are described for preventing false alarms due either to building disturbances or to ambient variations in temperature.

It is claimed that such a system would have economic advantages over other systems and that it could readily be adapted to give intruder protection.

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*Director, Joint Fire Research Organization, Ministry of Technology and Fire Offices' Committee.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
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LASER BEAMS IN TEMPERATURE GRADIENTS

The refractive index of air varies by about one part per million per degree Celsius rise in temperature and it has been suggested[1] that this variation might be used to detect fires in a number of ways using laser beams.

One method is to split the laser beam so that the two beams, one above the other, traverse horizontally the area to be protected near the ceiling.[2] As laser beams are coherent, they can be made to interfere on recombination - any change in refractive index in the vertical direction would cause a difference in the transit times of the beams, accompanied by a shift in the interference fringes. These changes in illumination can be recorded by a photo-cell and amplifier to give an alarm.

Another system[3] utilizes the deflection of a beam of light consequent on its traversing a field of varying temperature gradient above a fire. Because the variations in refractive index are only of the order of one per million per degree Celsius, the beam deflection is also small. A temperature gradient of 100°C per metre, for example, would cause the beam to follow a circular path of 10 km in radius and after traversing about 100 m, the deflections from fires are likely to be of the order of 10 mm. If a deflection of this magnitude is to be received and recorded by a photo-cell, it is necessary for the beam to be highly collimated. The spot of light after focusing the beam, should not be greater in linear dimensions than the deflection of the beam caused by the fire and a laser beam is necessary for this degree of collimation.

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In devising a fire detection system, it was decided to try the spot deflection system first.

BEAM COLLIMATION

Under 'no-fire' conditions a laser beam may be focused to form a spot at a remote distance by means of a telescope. The spot has a diameter $\frac{1.2}{a}\lambda l$, where λ is the wavelength of the laser (0.6328 microns for the helium-neon laser) a is the diameter of the objective used to form the image, and l is the distance of the laser from the spot. Over a distance of 100 m and with an objective of diameter 50 mm, the spot would have a diameter of $\frac{1.2 \times 0.6328 \times 10^{-3}}{50} \times 10^5$ mm, i.e. of the order of 1 mm. The theoretical spot size is difficult to attain because of lens imperfections and 5 mm would be a practical figure at this distance.

Even under quiet conditions the spot exhibits a slight movement of the order of a millimetre over a path of about 100 m.

LASER BEAMS ABOVE FIRES

Once a fire is lit under or to one side of the beam, the spot becomes violently agitated after a few seconds, the time lag depending on the height of the ceiling above the fire. This violent movement is a consequence of the turbulent plume of gas from the fire impinging on the ceiling and spreading out in much the same way as a torrent of water might strike and spread out over a floor. The turbulence causes the beam to deflect in a random manner about its rest position.

If the fire progresses, the space immediately under the ceiling fills with hot gas, rather as a bath fills with water, and the laser beam traverses a layer of hot gas which is now less turbulent, the turbulent region at this time having moved below the beam. The agitation of the spot is less violent and it moves as a whole from its original undisturbed condition. As this may take considerably longer than the first indication of turbulence in the spot, it is important to develop a detection system using the turbulent movement of the spot.[3] The deflection of the beam, d, would be expected to fall off with height of compartment, z, according to the law $d \propto z^{-2/3}$ (Appendix I). The size of fire necessary to operate the detector increases proportionally with z.

This method would be more advantageous than using thermal or point smoke detectors, whose response falls off much more rapidly (Appendix I).

DEFLECTING THE BEAM TO COVER AN AREA

If a simple detection system were constructed in which the beam from the laser traversed the space to be protected and was then received by a photo-cell, it would suffer from the disadvantage of the beam being more sensitive to fires near to the laser than near to the photo-cell because of the optical lever effect. (Fig. 1a).

The effect can largely be overcome by locating a mirror at the end of the protected space to return the beam on to a photo-cell placed near to the laser, so that the sensitivity due to the optical lever should never vary by more than a factor of 2 (Fig. 1b). This of course raises the problem of the stability of the mirror, for any slight angular change of the reflected beam due to the mirror mounting, would be magnified and recorded by the photo-cell as an alarm. Fortunately this can be overcome by using a 'corner-cube' mirror system, i.e. three mirrors mutually at right angles. Any ray of light incident on such a system, after reflection in the three mirrors, would be returned on a path parallel to the incident path, irrespective of the orientation of the mirror. (Fig. 2) and (Appendix II).

STABILITY CONSIDERATIONS

After removing variations in the position of the reflected beam due to the mirror mounting, there is always the possibility that the mounting of the laser itself might move slightly, causing the beam returning to the photo-cell to be displaced with the risk of a false alarm. This means that the size of the photo-cell must be large enough to cater for any movement of the beam. At first sight it would seem that to do this would cut down the sensitivity of the system, as the deflection of the spot would have to be greater for it to move off the larger photo-cell and so give the alarm. Advantage may be taken, however, of the fact that the agitation of the spot caused by a fire would be much more rapid than the very slow drift of the spot due to the movement of a building.

It has been suggested[4] that a checker-board mask with holes, each having a dimension about the size of the spot, should be put in front of the photo-cell receiver (Fig. 3). In its undisturbed state the spot might fall on a clear part of the photo-cell or be partially or wholly intercepted by the checker-board mask. Any slow drift of the spot would result in an output from the cell having a very low frequency which would be unable to be passed by the amplifier. A fire, on the other hand, would give a rapidly fluctuating signal which would be amplified to give an alarm. The checker-board mask could be extended to form a collimating mask, excluding extraneous light.

There is always a small amount of fluctuation of the beam caused by ambient changes arising from convection in the area to be protected, but O'Sullivan, Ghosh and Turner have shown[5] that these occur at a lower frequency than those associated with fires. Thus, if the amplifier is tuned to receive a frequency of 40-70 Hz, it is possible to discriminate against ambient fluctuations. A delay is also incorporated into the system to prevent false alarms, should the beam be momentarily interrupted.

SMOKE DETECTION

So far the problem of thermal detection has been described, but the system may be made sensitive to smoke by comparing the intensity of the beam which has traversed the area to be protected with the emitted beam (Fig. 4). Ghosh and O'Sullivan have suggested[6] that the checker-board mask might itself be a photo-cell in front of another continuous photo-cell. The checker-board photo-cell acts as a heat detector as previously described, while the sum of the outputs of the checker-board photo-cell and the one behind it together should give the intensity of the laser beam after traversing the area to be protected. This could be compared with the emergent intensity from the laser. (There is usually a low intensity beam from the back of the laser which could act as a reference).

INTRUDER DETECTION

It is easy to see that while the laser beam passing under the ceiling can be used to detect fires, part of the beam can, with a half-silvered mirror, be diverted to floor level and reflected so as to pass parallel to the floor and fall on to a separate photo-cell, which could be used to give an intruder alarm (Fig. 5). The laser beam is invisible until viewed almost along the line of the beam so that it is unobtrusive.

ECONOMIC CONSIDERATIONS

The cost of a helium-neon laser and power unit is about £160 and the guaranteed life is one year's continuous running. It is thought that the supply of lasers in quantity could reduce the price to about £100. The telescope, electronics and corner-cube reflector ought to cost about £100, so that the likely cost of the equipment is £200. A system installed in a building 41 m x 15 m x 12 m high (135 ft x 50 ft x 40 ft high) will detect a fire (711 mm (28 in) in diameter) in liquid fuel at any point in the building within half-a-minute. If the occupancy were sub-divided the laser beam could be arranged to traverse the building by drilling through the wall.

The equipment cost would therefore be about 7s. 0d. per square metre or 8d. per square foot.

The laser beam has no inertia and the delays are those of the rising plume of hot gas and smoke together with delays built into the system to prevent any adventitious alarm due to the beam being accidently interrupted.

CONCLUSIONS

It should be possible to use the perturbations and the absorption of a laser beam to provide a rapidly acting fire detector. The system should have an advantage over conventional systems in tall compartments due to the fact that the spreading plume is used to detect the fire and therefore the decrease in sensitivity with height of the compartment to be protected is less marked than with other systems.

The cost of the system should be less than that of existing systems and the problem of maintenance and testing should be much easier than with individual detector heads. A laser system is unobtrusive and does not involve unsightly detector heads and moreover it could be readily extended to give intruder protection. The cost of laser tubes has fallen rapidly recently and it is thought that commercially the system should be capable of still further cost reduction.

ACKNOWLEDGMENT

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APPENDIX I

VARIATION OF SENSITIVITY WITH HEIGHT - COMPARISON WITH OTHER SYSTEMS

If a beam of light is travelling in a medium of refractive index μ its path will be defined by:

$$\frac{d\mu}{\mu} = -\frac{dR}{R}$$

where R is the radius of curvature of the beam and μ the refractive index at any point.

As the changes in the refractive index of air above a fire are always very small, R is large and $\frac{d\mu}{dR}$ is very nearly $\frac{d\mu}{dz}$, where z is the distance in the vertical direction and in addition, since for gases $\mu \simeq 1$:

$$R = -\frac{1}{d\mu/dz} \qquad \text{........ (1)}$$

The variations in μ arise from variations in temperature above a fire and μ and T the temperature of the plume in K may be related by Biot and Arago's Law:

$$(\mu-1)T = \text{constant} \qquad \text{........ (2)}$$

$$\frac{d\mu}{dz} = -\frac{(\mu-1)}{T}\frac{dT}{dz}$$

Substituting for $d\mu/dz$ from equation (1):

$$\frac{1}{R} = \frac{(\mu-1)}{T}\frac{dT}{dz}$$

Therefore substituting for $(\mu - 1)$ from equation (1):

$$\frac{1}{R} = \frac{\text{const.}}{T^2}\frac{dT}{dz} \qquad \text{........ (3)}$$

For point sources, (e.g. a growing fire before detection) the temperature rise T_z at a distance z above the fire is given by Yih[7] as:

Since the plume expands uniformly in a horizontal direction, the beam of light will be refracted by the fire for a horizontal distance which increases uniformly with the height z of the beam. This will be the height of the compartment being protected as the beam is at ceiling height. From the geometry of the circle, the deflection of a beam moving in a circular path for a distance x is proportional to x^2/R. The deflection of the beam is hence proportional to:

$$\frac{Q^{\frac{2}{3}}\, z^2}{z^{8/3}} \quad \text{or} \quad \frac{Q^{\frac{2}{3}}}{z^{\frac{2}{3}}}$$

If the beam has to be deflected by a constant distance to give an alarm, then the heat output of the fire necessary for this will increase uniformly with the height of the beam above the fire.

OTHER SYSTEMS

The performance of a laser may be compared with that of a fixed-temperature-rise point detector situated above the fire.

From equation (4):

$$T \propto \left[\frac{Q^2}{z^5}\right]^{\frac{1}{3}}$$

For operation after a constant temperature rise:

$$\frac{Q^2}{z^5} = \text{constant} \quad \text{or} \quad Q \propto z^{5/2}$$

Therefore the size of fire necessary for operation increases rapidly with the height of the compartment to be protected. The same law for size of fire is also true for the rate-of-temperature-rise point detector. Thermal line detectors have a rather better performance with height of compartment because the plume expands uniformly as the height increases. Here the size of fire for operation varies as:

$$\left(\frac{z^{5/2}}{z}\right) \quad \text{or} \quad z^{3/2}$$

$$\frac{g\ T_z}{T_o} = 11 \left[\frac{Qg}{\rho_o\ c\ T_o} \right]^{\frac{2}{3}} \frac{1}{z^{5/3}} \exp \left\{ -71 \frac{r^2}{z^2} \right\}$$

or $$T_z = 11 \left[\frac{T_o}{g \rho_o^2 c^2} \right]^{\frac{1}{3}} \left[\frac{Q^2}{z^5} \right]^{\frac{1}{3}} \exp \left\{ -71 \frac{r^2}{z^2} \right\}$$

$$= k \left[\frac{Q^2}{z^5} \right]^{\frac{1}{3}} \exp \left\{ -71 \frac{r^2}{z^2} \right\} \qquad \text{.........} (4)$$

where Q is the rate of liberation of heat

r is the horizontal distance from the axis of the plume

$$k = 11 \left[\frac{T_o}{g\ \rho_o^2 c^2} \right]^{\frac{1}{3}}$$

and ρ_o, c and T_o are the density, specific heat and temperature of the air outside the plume respectively.

The exponential term in equation (4) expresses the fractional fall in temperature moving outwards from the axis of the plume and since r and z appear as a quotient, the plume expands uniformly with height. Therefore the temperature profile across the plume grows uniformly with height.

For small fires, the factor involving T^2 in equation (3) may be treated as constant,

and

$$\frac{1}{R} \propto \frac{dT}{dz}$$

At the centre of the plume, from equation (4):

$$\frac{dT}{dz} \propto \frac{Q^{\frac{2}{3}}}{z^{8/3}}$$

and the beam will follow a path of radius R,

where

$$\frac{1}{R} \propto \frac{Q^{\frac{2}{3}}}{z^{8/3}}$$

APPENDIX II

REFLECTIONS AT MIRROR SURFACES

SINGLE-MIRROR SYSTEM

If a beam of light is incident on a plane mirror, it will be reflected so that the incident and reflected beams make equal angles with the normal to the mirror, and the normal, incident and reflected beam are coplanar.

It is well known that if a mirror moves through an angle $d\alpha$ (Fig. 2a) the reflected beam will move through an angle $2d\alpha$ and at a distance D from the mirror, the deflection will be $2Dd\alpha$.

TWO-MIRROR SYSTEM

If a beam is incident on a two-mirror system so that it is reflected in both mirrors, the beam may readily be shown to be deviated through an angle $\phi = 2(\pi - \theta)$ (Fig. 6), where θ is the angle between the mirrors. When the mirrors are at right angles so that $\theta = \frac{\pi}{2}$, the beam will be deviated through an angle π, i.e. returned on a path parallel to the incident beam.

Since the angle of deviation ϕ is independent of the angle of incidence at the mirror, the beam will be returned, after reflection, parallel to the incident beam, irrespective of any rotation of the mirror system about the axis of the line of intersection of the mirrors. The reason for this is obvious; any rotation of the first mirror of the two-mirror system will just be compensated by an equal and opposite rotation of the second. Although the incident beam may be returned parallel to its original path, irrespective of the rotation of the mirror about the line of intersection, the reflected beam may nevertheless be displaced.

In practice both the line and laser detectors will have a rather better performance than is indicated here as the plume will spread out under the ceiling and will therefore influence the detector for a greater distance than the plume width.

Thus we have the following table of performance with height.

Type of detector	Variation of size of fire for operation with height
Laser	$Q \propto z$
Fixed-temperature-rise point detector	$Q \propto z^{5/2}$
Rate-of-temperature-rise point detector	$Q \propto z^{5/2}$
Thermal line detector	$Q \propto z^{3/2}$

From Fig. 6:

$$\frac{1}{\sin\,\theta} = \frac{L}{\sin\,(\theta+\alpha)} \qquad \ldots\ldots\ldots (4)$$

or $$1 \sin\,(\theta+\alpha) = L \sin\,\theta$$

where L may be as large as the side of the mirror.

Since L and θ are constants:

$$d\Big(1 \sin\,(\theta+\alpha)\Big) = 0$$

$$dl = \frac{1 \cos\,(\theta+\alpha)}{\sin\,(\theta+\alpha)}\,d\alpha$$

(Omitting the minus sign as we are only concerned with sizes).

Substituting for 1 from equation (4):

$$dl = L\,\frac{\sin\,\theta\,\cos\,(\theta+\alpha)}{\sin^2\,(\theta+\alpha)}\,d\alpha$$

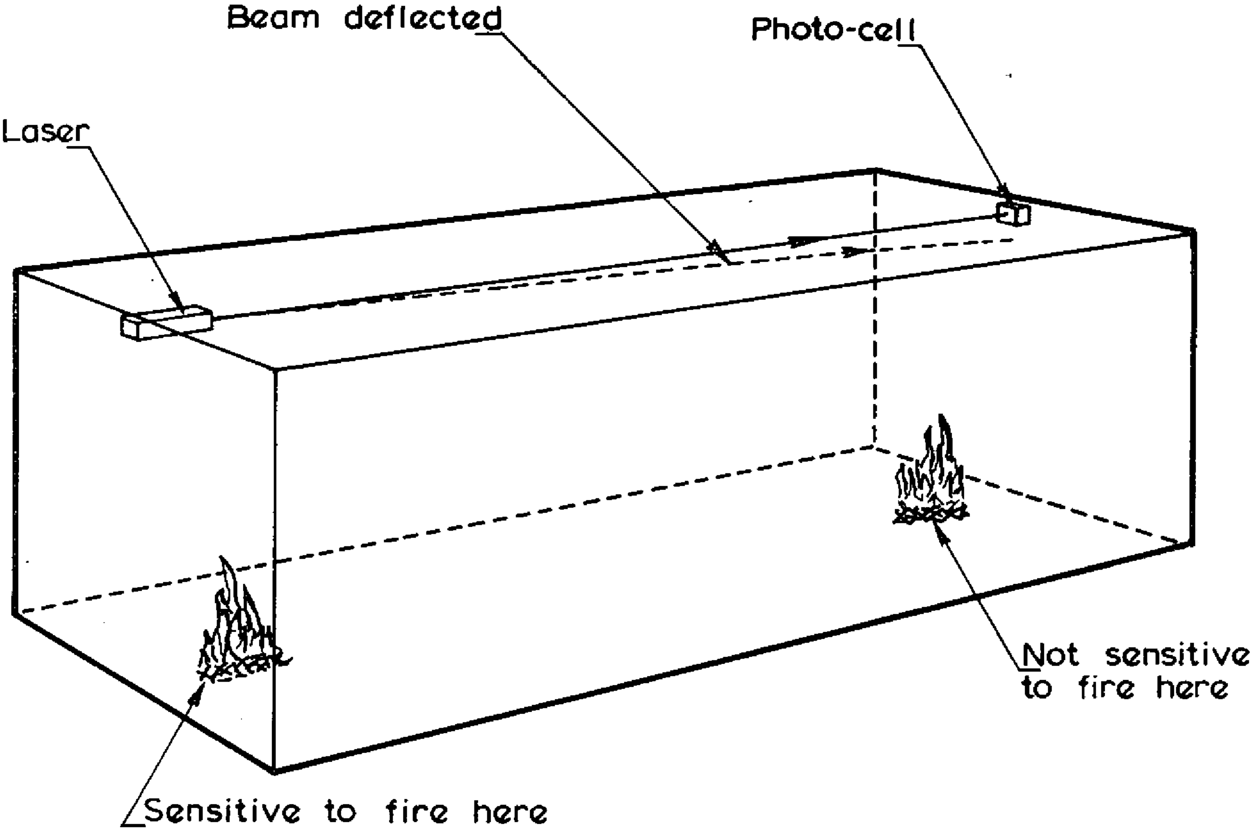
Now if $\theta = \frac{\pi}{2}$, the condition for the beam being returned parallel to its own path, then α will be about $\frac{\pi}{4}$ and the displacement of the beam roughly $1.4\,Ld\alpha$. Thus a rotation of the mirror system which in effect alters α, only produces a deviation of $1.4\,Ld\alpha$. This may be contrasted with the single mirror which at a distance D produces a deviation of $2Dd\alpha$. The improvement is thus of the order of $0.7\,\frac{L}{D}$. Now since the aperture of a dihedral mirror may be, say, 100 mm, then if D, the length of the beam over the area to be protected, is say 50 m, the stability of a two-mirror system is some 300 times that of a single-mirror system. Of course the two-mirror system only stabilizes the beam for rotations about the axis of intersection of the mirrors. It behaves as a plane mirror for rotations at right angles to the line of intersection.

Thus for the general case of a rotation $d\alpha$ and $d\beta$, as shown in Fig. 7, the resultant displacement of the beam at a distance D would be about $(2\,L^2\,d\alpha^2 + 4\,D^2\,d\beta^2)^{\frac{1}{2}}$.

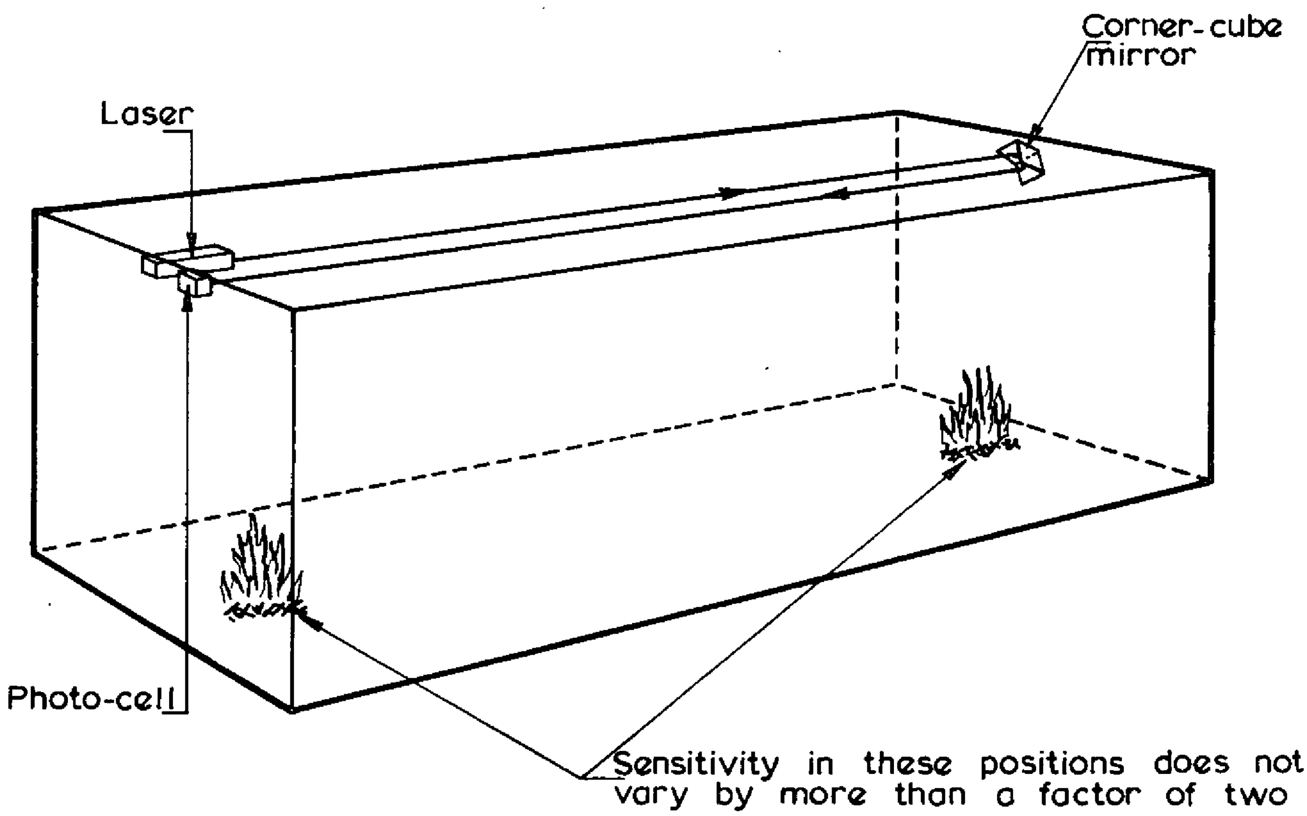
THREE-MIRROR SYSTEM (CORNER-CUBE REFLECTOR)

Three mirrors mutually at right angles have the property of reflecting an incident beam so that it is parallel to the incident direction, irrespective of the rotation of the mirror. From the discussion of the rotation of the two-mirror system, it was seen that any rotation could be resolved into a rotation around the line of intersection of the mirror which caused no deflection of the beam and one at right angles which caused the beam to vary as for a single-mirror reflection. Now with a three-mirror system the rotations at right angles to the intersection of mirrors 1 and 2 will be around the axis of the lines joining mirrors 2 and 3 and thus the unstabilized reflection becomes stabilized after reflection in mirror 3. This is only true when the mirrors are mutually at right angles (Fig. 2c). The three-mirror system is thus only stabilized against rotations when the mirrors are mutually at right angles.

As before, displacements can occur in the beam and, for small angular variations $d\alpha$ and $d\beta$ at right angles, these will be $1.4\,L\,(d\alpha^2 + d\beta^2)^{\frac{1}{2}}$ where L is the side of the corner cube.



(a) Single beam has defect of variable sensitivity



(b) Reflected beam causes less variation in sensitivity

FIG. 1. VARIATION OF SENSITIVITY OF LASER FIRE DETECTOR WITH POSITION

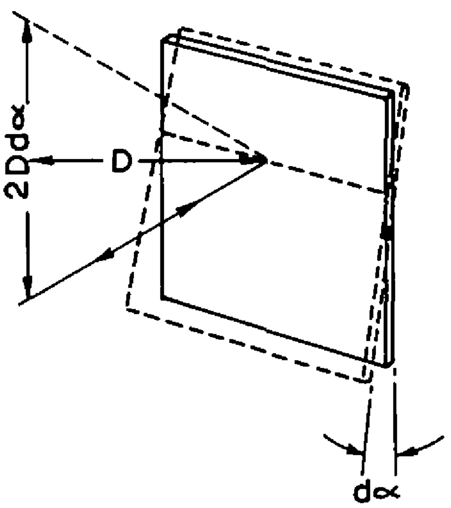


FIG. 2a. SINGLE MIRRORS IF MOVED GIVE LARGE DEFLECTION OF BEAM

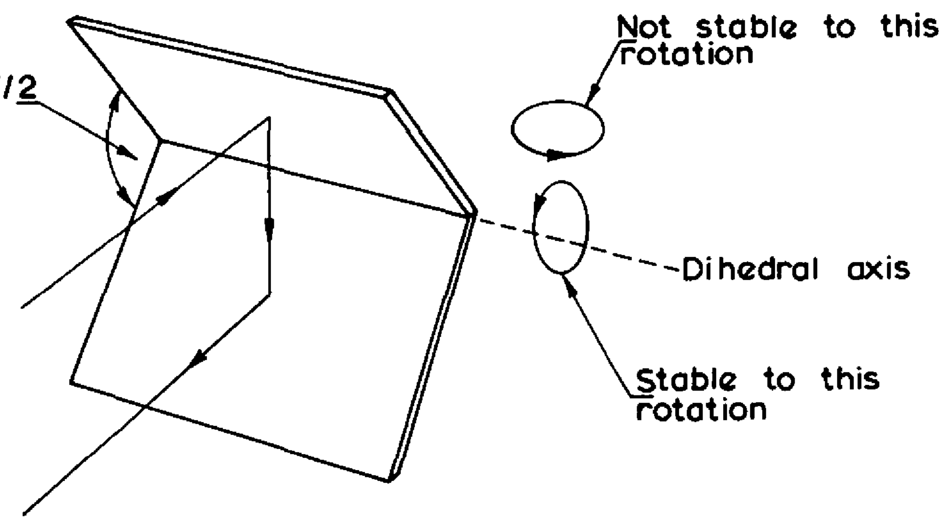


FIG. 2b. TWO MIRRORS MUTUALLY AT RIGHT ANGLES WILL ALWAYS RETURN A BEAM PARALLEL TO THE INCIDENT DIRECTION IRRESPECTIVE OF ROTATION ABOUT THE DIHEDRAL AXIS

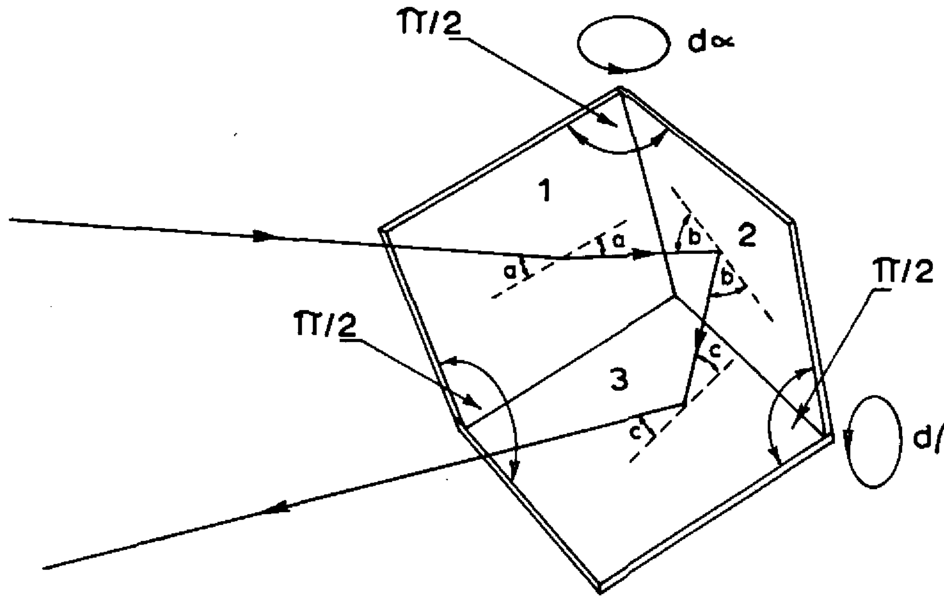


FIG. 2c. CORNER-CUBE MIRROR SYSTEM. MIRRORS MUTUALLY AT RIGHT ANGLES. EMERGENT BEAM ALWAYS PARALLEL TO INCIDENT BEAM NO MATTER HOW CUBE IS ROTATED

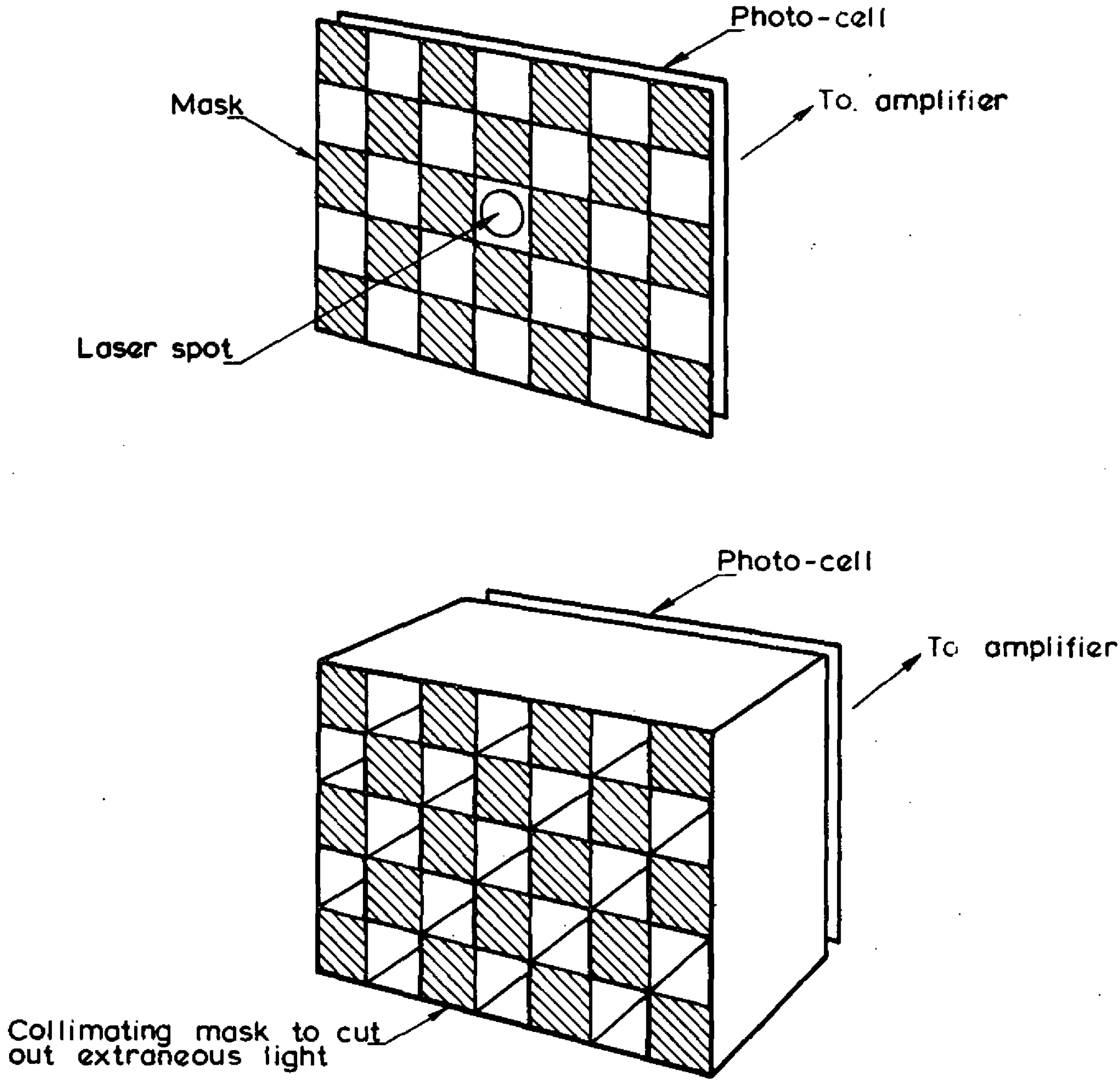


FIG. 3. PHOTO-CELL MASK

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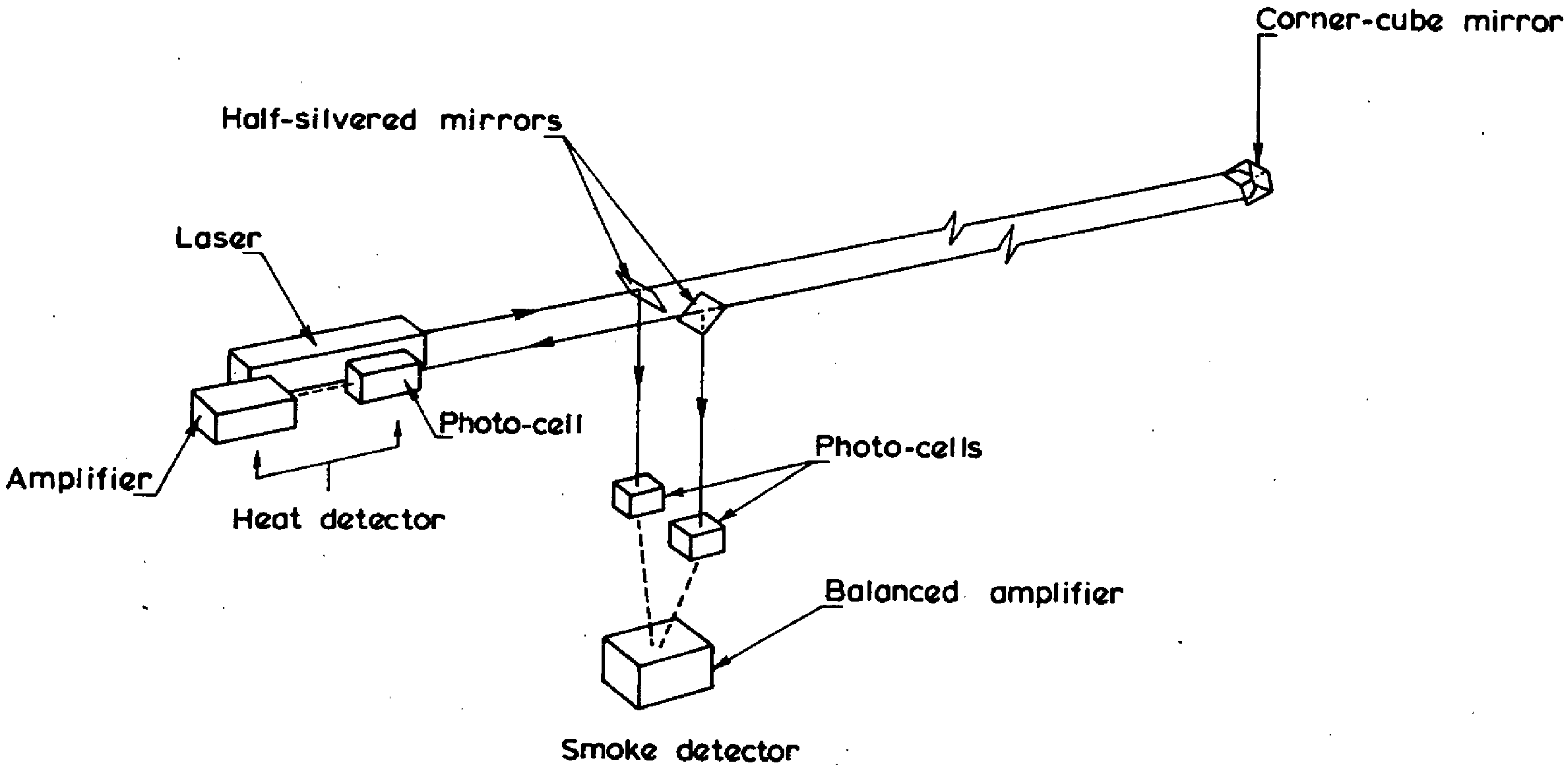

FIG. 4. SYSTEM FOR HEAT AND SMOKE DETECTION

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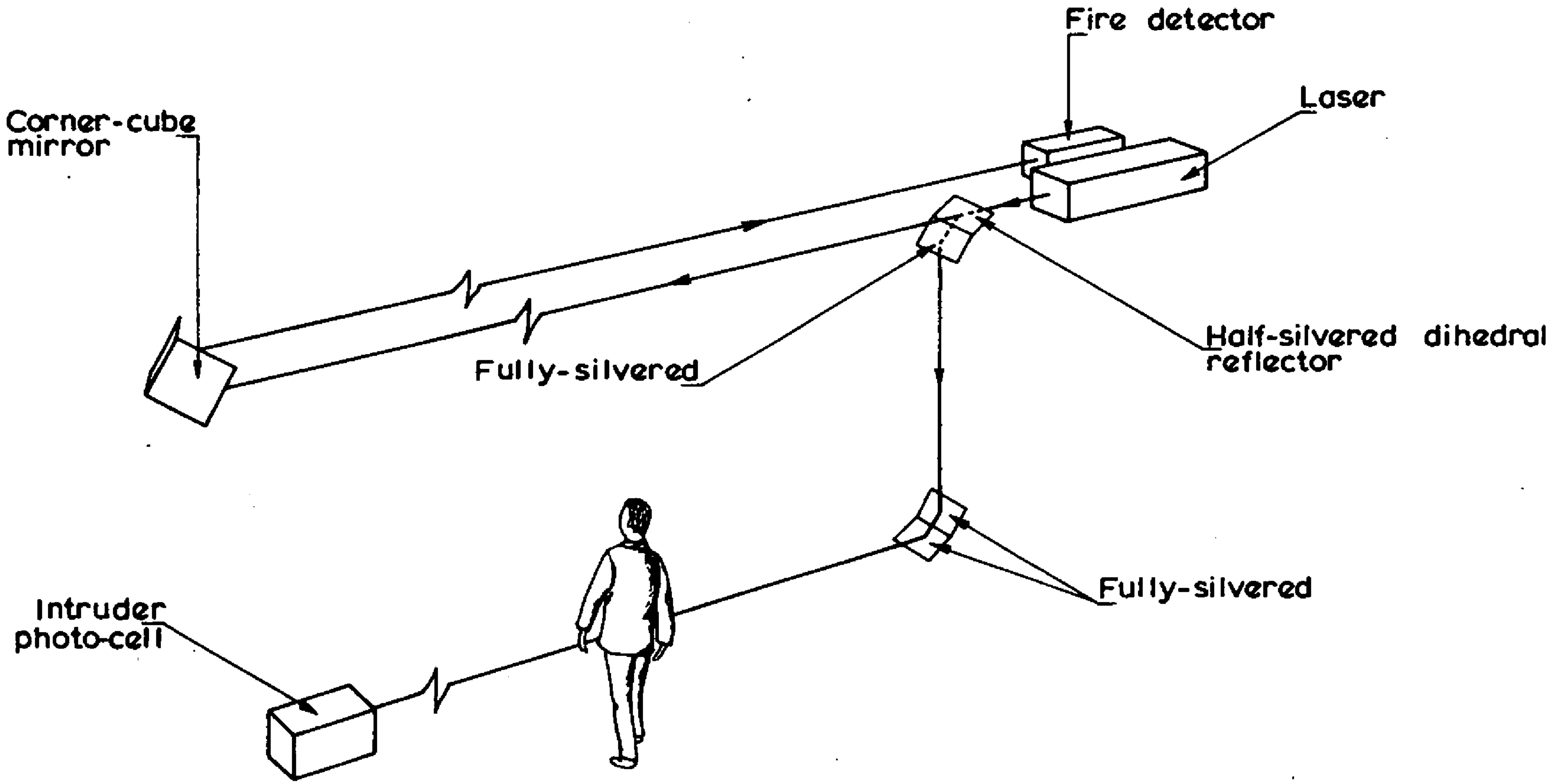


FIG. 5. COMBINED FIRE AND INTRUDER PROTECTION SYSTEM

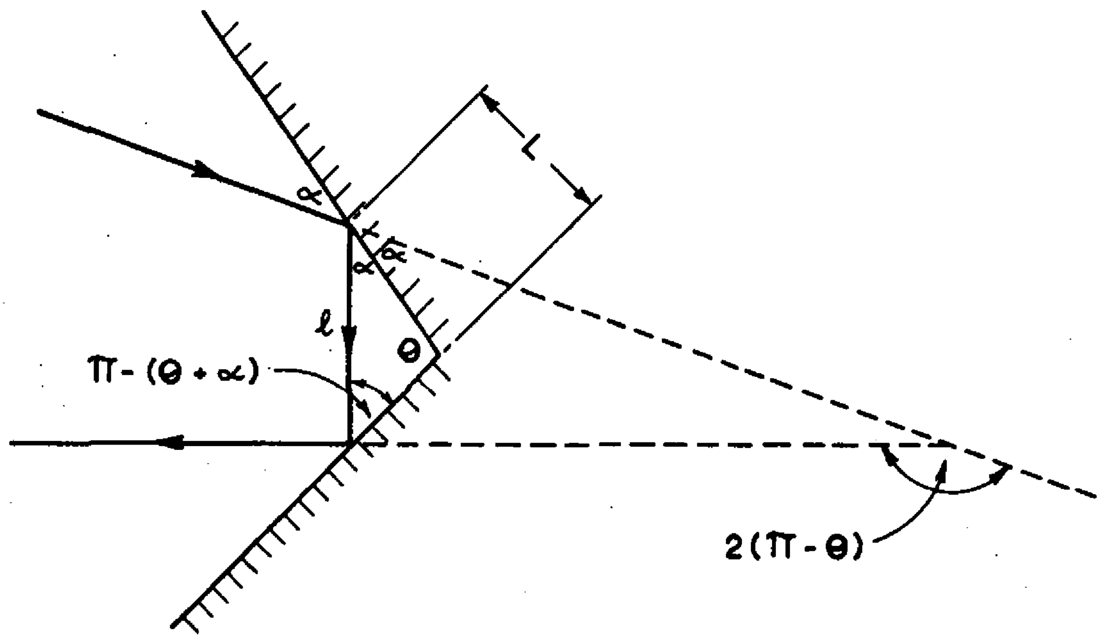
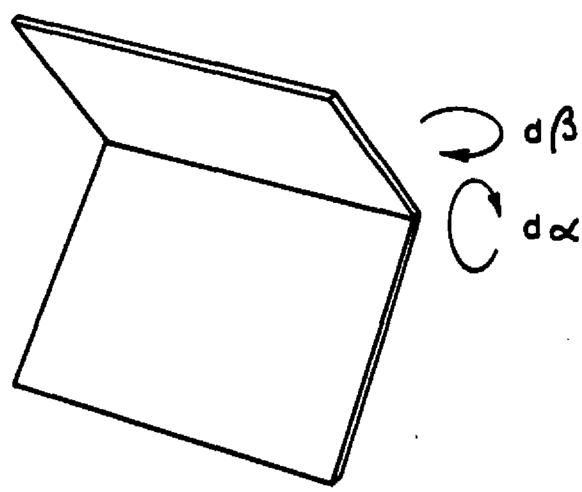


FIG. 6. REFLECTIONS FROM A TWO-MIRROR SYSTEM



dα is the rotation about the dihedral axis
dβ is the rotation at right angles to this

FIG. 7. ANY ROTATION OF A TWO-MIRROR SYSTEM MAY BE RESOLVED INTO TWO ROTATIONS