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R. ADLER ET AL
SOLID STATE MATRIX HAVING AN INJECTION LUMINESCENT DIODE
AS THE LIGHT SOURCE
Filed April 29, 1968

3,501,676

FIG. 1

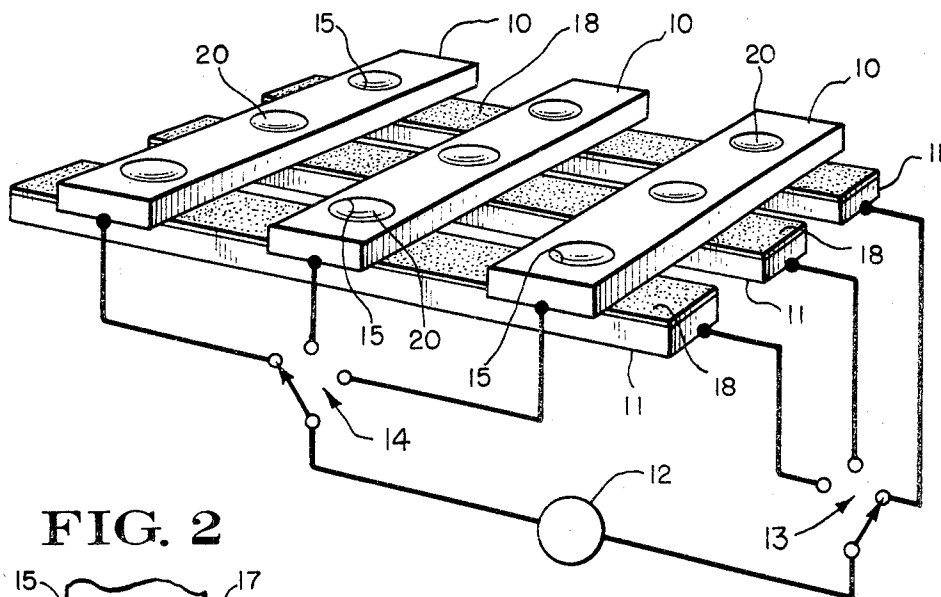


FIG. 2

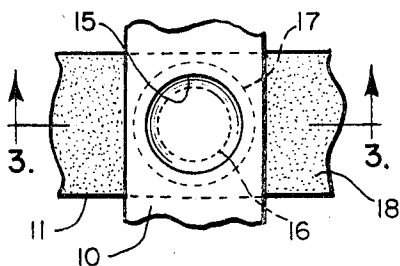


FIG. 3

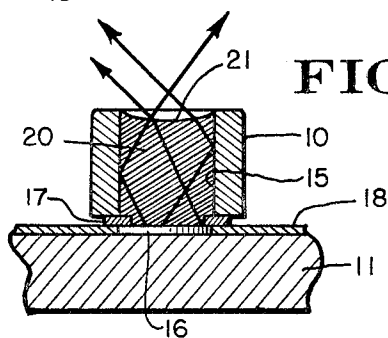


FIG. 4

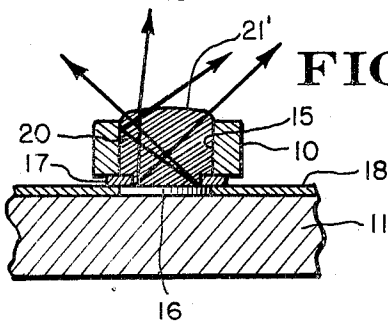
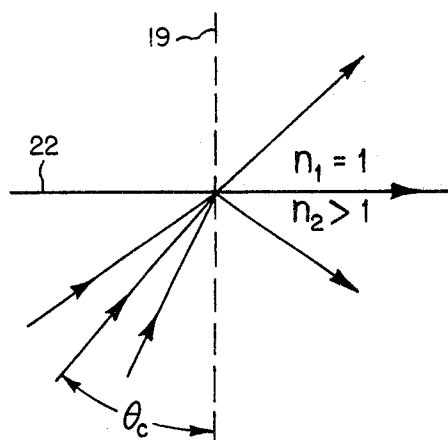


FIG. 5



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SOLID STATE MATRIX HAVING AN INJECTION LUMINESCENT DIODE AS THE LIGHT SOURCE
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7 Claims

ABSTRACT OF THE DISCLOSURE

An image-display panel is composed of a matrix of electrically-conductive strips running in one direction across a plurality of electrically-conductive ribbons. At each intersection between a ribbon and a strip, a light source, exemplified by an injection-luminescent diode, is disposed within an aperture in the strip. The light source terminals are electrically connected to the strip and to the ribbon respectively at the cross-point where the light source is situated. Each of the apertures is filled with an insert having an index of refraction between those of the light source and air and preferably presenting a curved surface to the air. The insert is formed by initially filling the aperture with a liquid material and then solidifying it to form the insert, and the meniscus of the liquid state material provides the preferred curved outer surface upon solidification. Preferably, the front surfaces of the strips and ribbons are blackened to improve image contrast.

Background of the invention

The present invention pertains to optical radiation emitting apparatus. It is particularly of interest with respect to the construction of solid-state image display panels.

Numerous proposals have been advanced for the reproduction of images by the use of crossed arrays of conductive elements having some kind of light-emitting device at or near each intersection of the respective elements in the two different arrays. The light sources are energized by a potential or current appearing or available between the two elements at any one intersection, and by selectively switching between the different elements in each of the arrays it is possible to select which one or ones of the intersections carry the necessary energizing potentials at any instant. Perhaps the longest span of attention has been devoted to the use in such apparatus of an electroluminescent phosphor material as the source of light. However, at least most such approaches have not been entirely satisfactory for many different reasons, including excessive decay time, insufficient discrimination between different ones of the intersections and presentation to the energizing circuitry of a very high value of capacitance.

More recently, interest has been given to the injection-luminescent diode for use in somewhat similar systems. Such diodes are solid-state devices which emit light in response to the application of energizing currents. It has been heretofore proposed to dispose one such diode near or at each of the intersections in a crossed-array-type matrix, and to supply the currents to the different individual diodes by selective energization of the various elements in each array. At least usually, injection-luminescent diodes are fabricated from materials which have large indices of refraction as compared with that of air, which has an index of refraction of unity. Since air is the typical medium in which such diodes operate, the large index of refraction of the diode material results in the existence at the interface of a small critical angle of reflection from the material to the air. This in turn means that a large quantity of the total light generated within the diode is internally reflected and thus not available for utilization outside the diode.

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As described in "GaAs Light Era on the Way" by J. R. Baird and Hans Strack, Electronics, vol. 40, No. 23, Nov. 13, 1967, attempts have been made to increase the amount of light transmitted through the interface by disposing the diode within a hemisphere of some other material also having a high index of refraction as compared to that of air. Consequently, by lowering the difference in indices of refraction as between the diode material and that of the hemisphere, more light is enabled to be emitted from the diode itself. Further, as viewed from any particular direction to the diode, the curved surface of the hemisphere has a geometry which enables more of the light to arrive at the interface, between it and the surrounding medium, at such an angle that it traverses that interface. At the same time, however, the material of the hemisphere can pose difficulties in handling, assembly and device fabrication and from the light absorption in that material.

Summary of the invention

It is, accordingly, one general object of the present invention to provide new and improved radiation emitting apparatus which achieves the aforementioned improved emission efficiency in the presence of diverse indices of refraction, while being capable of being manufactured very simply and directly and of avoiding or lessening the above-noted difficulties.

Another object of the present invention is to provide new and improved apparatus of the foregoing character in which there is an increase in the proportion of potentially available radiation from the source that actually is realized.

Light emitting diodes of the kind under discussion are often excited with short pulses of high-intensity current. Yet typical suggestions for their use in display panels involve thin-film fabrication techniques for constructing at least one of the connecting electrodes, that one which often must be transparent. Presenting a high resistance and inductance, the resulting small-area conductors basically are inconsistent with the use of high current levels.

Consequently, a still further object of the present invention is to incorporate light sources of the aforementioned character in a display arrangement in which the series impedance presented to the energizing current is materially reduced.

Radiation emitting apparatus constructed in accordance with the present invention includes means defining an aperture at least one end of which is disposed in a medium having a predetermined index of refraction to optical radiation. An optical radiation source in alignment with the aperture includes a material, from which the radiation is emitted, that has an index of refraction to the optical radiation higher than the predetermined index of refraction. Finally, a radiation-transparent element, having an index of refraction to the radiation also higher than the predetermined index of refraction, is disposed in alignment with the aperture in contact with the source; the element has a meniscus-shaped surface exposed to the medium. The invention also contemplates forming the apparatus by disposing in the aperture, between the medium and the material of the source, a column of the liquid element which forms, in cooperation with the wall of the aperture, the meniscus which is exposed to the medium. Subsequently, the element is solidified while preserving the shape of the meniscus.

Brief description of the drawing

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The organization and manner of operation of the invention, together with further objects and advantages thereof, may best be understood by reference to

the following description taken in connection with the accompanying drawing, in the several figures of which like reference numerals identify like elements, and in which:

FIGURE 1 is a simplified perspective view of an image display matrix which embodies the invention, including a schematic representation of energizing circuitry therefor;

FIGURE 2 is a plan view of a portion of the apparatus shown in FIGURE 1;

FIGURE 3 is a fragmentary cross-sectional view taken along the line 3—3 in FIGURE 2;

FIGURE 4 is a fragmentary cross-sectional view of an alternative form of that portion of the apparatus illustrated in FIGURE 3; and

FIGURE 5 is a diagram useful in explaining certain characteristics of the apparatus depicted in the other figures.

Description of the preferred embodiment

FIGURE 1 depicts, in highly simplified form for purposes of clarity, an image display device composed of a first array of laterally-spaced electrically-conductive strips 10 and a second array of laterally-spaced electrically-conductive ribbons 11 oriented at right angles to strips 10. A current source 12 is selectively connectable to different ones of the elements in each of the arrays through switches 13 and 14. Thus, with the switches positioned as shown in the drawing, the current from source 12 is available between the rear-most one of ribbons 11 and the left-most one of strips 10; it is immediately available at the intersection between that strip and that ribbon at the upper left-hand corner of FIGURE 1. By selectively changing the positions of either or both of switches 13 and 14, different ones of the strip-ribbon intersections may be chosen as the cross-point in the matrix at which the current appears.

The particular mode of intersection selection illustrated in FIGURE 1 is most rudimentary. However, the prior art is replete with numerous schemes for achieving selection in a more sophisticated manner and in connection with matrices having many hundreds and even thousands of such selectable intersections. In one approach, the different electrodes of an array are connected individually to successively spaced points along a transmission line down which a pulse of energy is caused to travel and thus successively to be applied to successive ones of the electrodes. By similarly causing such sequential energization in one direction along one of the arrays and in a direction at right angles thereto along the other array, it is known to so correlate the two different directions of scan that an image may be formed in the manner of a television display. The present discussion, however, is directed primarily to the manner of deriving optical radiation, such as light, from each of the individual intersection points. Consequently, although of interest with respect to the radiation produced at all of the points, it is sufficient for further purposes to focus attention upon but a single intersection between one of strips 10 and one of ribbons 11. In passing, it may also be noted that the term "optical radiation" as employed herein is intended to embrace light in either the visible or the invisible (e.g., infra-red or ultra-violet) regions of the spectrum. However, for convenience the description will proceed on the basis of visible light radiation.

FIGURE 2 represents one intersection between a strip 10 and a ribbon 11 at which light is selectively to be developed or produced. Formed in strip 10, over ribbon 11, is an aperture or tubular element 15 having a polished inner wall. In alignment with tubular element 15 is an optical radiation source 16, preferably physically mounted upon the surface of ribbon 11 directly beneath aperture 15. While the arrangement as thus far described, and as to be further discussed, also finds applicability with various kinds of light sources, source 16 in this

instance preferably is an injection-luminescent diode. Such light-producing devices are described in the article entitled "Radiation Recombination in the III-V Compounds" by M. Gershonzon in the book *Semiconductors and Semi-metals*, vol. 2, edited by R. K. Willardson and Albert C. Beer, and published by Academic Press in 1966, as well as in the aforementioned article in *Electronics*; highly efficient visible light emitting injection luminescent diodes and their fabrication are described in detail in a copending application Ser. No. 661,866 of Robert J. Robinson filed Aug. 17, 1967 for "Solid State Light Sources," which application is assigned to the present assignee.

It is sufficient for present purposes to note that diode 16 is a solid-state device which functions to emit light in response to an electric current conducted through its two connecting terminals. Such terminals may take the form shown in FIGURE 3 in which they are composed of electrically conductive films integral with opposing surfaces of the diode. Thus, the bottom surface of diode 16 as shown in FIGURE 3 constitutes such a film and is in direct electrical contact with the upper surface of ribbon 11. An electrically-conductive annular member 17 serves to couple the film on the upper surface of the diode to strip 10; an insulating layer 18, between ribbon 11 and member 17 and through which diode 16 is disposed, is here included to insure electrical separation between the parts. Alternatively, diode 16 itself may have a size relative to aperture 15 such that strip 10 makes direct contact with the conductive film on the upper diode surface.

In operation, when switches 13 and 14 of FIGURE 1 are so positioned that both strip 10 and ribbon 11 of FIGURES 2 and 3 are energized, current is caused to flow through diode 16 of a magnitude sufficient to cause the diode to emit light. By modification of the switching arrangement, more than one intersection in the FIGURE 1 matrix may be simultaneously energized when desired for particular display modes. As is true in some prior matrix-type display systems, the desired energization of a diode at a selected intersection may, because of leakage impedances in the light sources, cause some potential to be developed across diodes located at others of the intersections. To avoid or minimize such spurious energization of light sources at other cross-points, it is preferable that the individual light sources exhibit a sharply non-linear light-output vs. energizing-potential characteristic. The described injection-luminescent diodes operate in accordance with such a characteristic.

Returning to the assembly shown in FIGURE 3, tubular element 15 is filled with an insert 20, transparent to light, in contact with and covering diode 16 at one end of the aperture and at the other end having a meniscus-shaped surface 21 exposed to the external medium which typically is air. Insert 20 is composed of a transparent material whose index of refraction is higher than that of air and lower than that of the diode light source, preferably as nearly as possible equal to the geometric mean between the two. In the fabrication of the device, aperture 15 is first caused to be defined or formed in strip 10, as by drilling a hole, and the aperture wall then preferably is polished so as to be highly reflective to light emitted from diode 16. The diode is affixed to the upper surface of ribbon 11 after which member 17 is located in place and strip 10 is disposed across strip 11 with aperture 15 aligned over member 17 and the diode. As shown, member 17 is sufficiently larger than the diameter of aperture 15 to allow for some misregistration during assembly while yet achieving good electrical contact. The latter also is facilitated by coating one or more of the connecting surfaces with a low-melting-point solder and, during fabrication, heating the assembly with the parts pressed together so as, on subsequent cooling, to obtain both mechanical and electrical bonds. Finally, insert 20 is introduced within

the aperture in liquefied form so that, in cooperation with the wall of aperture 15, a meniscus of a shape corresponding to that desired for surface 21 is formed. Subsequently, the initially liquefied material of insert 20 is permitted or caused to solidify while the other components are held stationary so as to preserve or maintain the shape of the meniscus 21 and hence of the outer surface. In an exemplary device, strip 10 and electrode 11 are formed of copper, while inserts 20 are formed of an epoxy or other plastic material; vinylidene chloride, polyvinyl chloride and poly(vinyl chloride-vinyl acetate) are specific examples of useful plastic materials.

As shown in FIGURE 3, surface 21 is concave. Alternatively, it may be convex as in the case of surface 21' of insert 20' in FIGURE 4. Otherwise, the embodiments of FIGURES 3 and 4 are structurally the same. Generally speaking, a concave meniscus is formed when the liquid material used in forming insert 20 wets the wall of aperture 15. That, in turn, is a function of the materials of the wall and the element, the surface finish of the wall, the rate of solidification of the different regions within insert 20, the amount of any hardener which may be included in the material of insert 20, the temperature of insert 20 when liquid and the rate of change of the temperatures of the parts during solidification. In most cases, a generally curved and non-planar surface 21 or 21' is formed.

Diode 16 is fabricated from a material having a large index of refraction to the light it produces; for example, the index of refraction of gallium arsenide phosphide, an illustrative injection diode material, is approximately 3.5. Consequently, if the diode were simply disposed in air, the material from which the light must come would form an interface with the air dividing two regions having a large difference in their respective indices of refraction. Under such a condition, the light approaching that interface must form an angle to the normal comparatively small in order to be translated through the interface. This phenomenon is illustrated in FIGURE 5 in which the line 22 represents the interface between air, which has an index of refraction, n_1 , equal to one, and another region in which the index of refraction n_2 is much greater than one. Dashed line 19 represents a normal to the interface. That which is called the critical angle θ_c , as measured from the normal, is defined by the relationship

$$\theta_c = \sin^{-1} \frac{n_1}{n_2}$$

Light incident upon the interface from the denser medium (the one with the higher index of refraction) is totally reflected when it arrives at an angle greater than the value of θ_c . Light so incident precisely at the critical angle is refracted in a direction parallel to the surface. Only that light which approaches the interface at an angle less than the critical angle θ_c exits from the higher-density material to the lower-density material, in this case to the air.

Consequently, when a device such as diode 16, being itself made of a material having a relatively high index of refraction, must emit its light directly into air, the equation set forth above reveals that the critical angle is comparatively small. As a result, light approaching the interface from within the diode at greater than that small angle is reflected internally and thus is not available. On the other hand, by covering the light-emitting surface of diode 16 with transparent insert 20 having an intermediate index of refraction, the equation reveals that the critical angle becomes such larger so that a substantially greater quantity of light is permitted to leave diode 16. In some cases, depending on the geometry of the configuration, including both the orientation of the polished inner wall of tubular element 15 and of surface 21, the provision of a curved exit surface enables a substantially greater portion of the light to be emitted to the surrounding air medium than obtained with the use of a flat exit surface.

FIGURE 3 shows the paths of illustrative light rays

from diode 16 when insert 20 has a concave exit surface 21 while FIGURE 4 shows illustrative light paths with a convex exit surface 21. The best exit surface configuration is dependent on the geometry of the assembly, including the depth and the diameter of tubular element 15, upon the reflectivity of the internal surface of tubular element 15 and the transmission loss coefficient of insert 20, and upon the specific indices of refraction of diode 16 and insert 20, and can be readily ascertained either empirically or by computation in any given embodiment. In any case, the external radiation efficiency with a transparent insert 20 having an intermediate index of refraction may be substantially greater than that obtained without the provision of such an insert. In general, a convex exit surface is preferred if the depth of tubular element 15 is less than its diameter, while a concave surface gives better external radiation efficiency if tubular element 15 is deeper than its diameter.

The material from which insert 20 is formed may with some advantage have an index of refraction anywhere intermediate that of the air and that of diode 16. To the extent that this index is higher than that of the air, it increases the amount of light permitted to escape from the diode and also creates at interface 21 a smaller index ratio so as to define a larger critical angle. For example, if the index of refraction of the diode material is 3.5, all light arriving at the surface of the diode at angles greater than 16.65° is reflected back into the diode. However, if the material of insert 20 has an index of refraction of 1.6, light generated in the diode and incident on the interface between the diode and element 20 at angles less than 27.29° will be emitted into element 20. Together with the favorable shape and the reflections off the aperture wall, a substantial portion of the emitted light thus is permitted to escape into the surrounding air. In the present example, light arriving at surface 21 or 21' at angles of less than 38.7° to the normal will be transmitted into the air, and the external efficiency of the system is improved. If desired, a quarter-wave optical matching section may be provided between the light emitting surface of diode 16 and insert 20 or at surface 21. In a manner well known as such, the matching section increases the amount of radiation transferred between materials having different refraction indices. It also is known to form such matching sections as layers deposited, in this case on the upper surface of diode 16 or on surface 21, by usual methods of vacuum evaporation.

The wall of aperture 15 may be slightly tapered or curved so as to define a section, for example, of a cone, in order even better to cooperate with the curved shape of surface 21 for certain configurations and comparative widths of the particular diodes employed. Of course, the precise amount and direction of any such taper must be determined in view of the diode selected by means of plotting ray paths from the diode to the actual meniscus shape obtained with a given selection of materials. While as illustrated in FIGURES 3 and 4, diode 16 is situated on ribbon 11 beneath strip 10, the diode may protrude at least slightly inside the wall of aperture 15. However, it is preferred that the spacing between the light-emitting surface of diode 16 and surface 21 be sufficiently great to take advantage of the already-discussed reflection of light from the aperture wall.

As thus far considered, diode 16 has taken the form of a discrete element within the assembly. It may instead be formed as an integral part of ribbon 11. In one example, ribbon 11 is composed of a semiconductive material such as gallium arsenide phosphide. The individual diodes are spaced along the ribbon at the intersections with strips 10, each diode constituting a P-N junction formed in the material of the ribbon by conventional techniques as exemplified in the heretofore-reference articles. Of course, all of the diodes in a ribbon may be so formed at the same time. To improve conductivity of ribbon 11 itself, as well as to reduce overall materials costs, it also is contem-

plated to form the series of diodes in a single, preferably thin, ribbon of the semiconductive material bonded to a thicker base of copper or other high-conductivity metal.

Returning again to a consideration of the overall assembly of FIGURE 1, the surfaces of strips 10 and ribbons 11 facing the viewer preferably are rendered absorptive of light. In this manner, ambient light is substantially prevented from being reflected toward the viewer, while the light emitted from apertures 15 is permitted to travel toward the viewer without restriction. As a consequence, the overall image contrast is enhanced. To these ends, the exposed frontal non-emitting surfaces are painted or otherwise coated with a light absorbing material like a flat black paint. In the case of ribbon 11 in FIGURES 2 and 3, insulating layer 18 also may serve as the light absorber. Further implementing this approach, the entire areas of the spaces between strips 10 may be occupied by a light absorbing sheet. With the exposed surfaces of strips 10 treated so as likewise to be light absorbing, the entire display area is rendered non-reflective except for apertures 15 from which the desired light is emitted.

Since apertures 15 pass the light produced by diodes 16 to the viewer without obstruction by the energizing electrode material of strips 10, the latter advantageously may be of large cross-sectional area, with their thickness of the same order of magnitude as their width (i.e., width and thickness differing by a factor of 10 or less), and of a material having a high electrical conductivity. These characteristics result in less resistance and inductance in strips 10 as well as in ribbons 11. Consequently, the series impedance between source 12 and diodes 16 is minimized with a corresponding reduction in energizing voltage drop and power loss. As pointed out in the introduction, this feature is especially attractive with respect to the use of the injection-luminescent diodes, because the latter typically are energized with short-duration high-current pulses.

In reviewing several of the various features, it may be observed that insert 20 with its curved surface 21 functions as a lens to select and pass a maximum of the light emitted directly from element 16 and the light reflected from the wall of aperture 15. Moreover, the entire arrangement is readily adapted to mass production techniques; as indicated, the lens inserts may be formed by pouring and setting appropriate material and the diodes may be formed by producing a plurality of junctions along strip arrays of base material. The techniques illustrated and described permit the use of a large portion of the light developed within a device such as an injection luminescent diode, while yet doing so in a manner which is both simple and easy to achieve. High contrast performance may be had while at the same time obtaining maximum brightness. The construction also admits of high efficiency in the energization of the light sources.

We claim:

1. A solid state matrix-type image display panel comprising:

first and second crossed sets of mutually insulated electrical conductors at least the first set of which is composed of conductors of a thickness of the same order of magnitude as their width;

the conductors of said first set being provided with

a plurality of internally reflecting apertures respectively extending therethrough at cross-points between the conductors of said first and second sets;

a plurality of two-terminal electric-current-responsive light sources in juxtaposition with respective ones of said apertures;

means electrically connecting one terminal of each of said light sources with the conductor of said first set containing the aperture with which such light source is juxtaposed and electrically connecting the other terminal with the conductor of said other set at the cross-point associated with such aperture;

and respective inserts of light-transmissive material having a refractive index greater than unity substantially filling said apertures.

2. A solid state matrix-type image display panel according to claim 1, in which said inserts of light-transmissive material have a refractive index intermediate that of said light sources and that of air.

3. A solid state matrix-type image display panel according to claim 1, in which said inserts of light-transmissive material have curved exit surfaces for light rays originating at said light sources.

4. A solid state matrix-type image display panel according to claim 3, in which the tubular elements constituted by said apertures individually have a depth greater than their diameters, and in which said curved exit surfaces are concave.

5. A solid state matrix-type image display panel according to claim 3, in which the tubular elements constituted by said apertures individually have a depth less than their diameters, and in which said curved exit surfaces are convex.

6. In combination:

a source of optical radiation composed of a material having a refractive index substantially greater than unity;

and means for improving the external radiation efficiency of said source comprising (a) an internally reflective tubular element in juxtaposition with said source and (b) a light-transmissive insert having a refractive index greater than unity and substantially filling said tubular element and in optical contact with said source.

7. The combination according to claim 6, in which said light-transmissive insert has a refractive index less than that of said source of optical radiation.

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