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[54] **SOLID-STATE IMAGE INTENSIFIER**

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[51] **Int. Cl.**..........................**H01j 39/00,** H05b 37/00

[58] **Field of Search**..315/169, 169 TV, 175; 313/94, 313/108 A

[56] **References Cited**

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[57] **ABSTRACT**

A solid-state image intensifier comprising, essentially, an electroluminescent layer containing 45 to 70 percent by volume of electroluminescent phosphor mixed with a binding material and a photoconductive layer in juxtaposition or close association with the electroluminescent layer. This solid-state image intensifier is adapted for use as an amplifier of radiant energy or as a converter of invisible radiation into visible radiation and is designed to be energized by AC and DC fields. Due to its pecific composition, the electroluminescent layer has a nonlinear resistance which functions to keep a DC voltage applied across the photoconductive layer at a substantially constant value, thereby increasing the photoconductive sensitivity of the photoconductive layer. The increase in the DC voltage as applied to the image intensifier causes the characteristic curve to shift to the low input energy side, enabling efficient operation of the image intensifier in a low input energy range.

9 Claims, 5 Drawing Figures

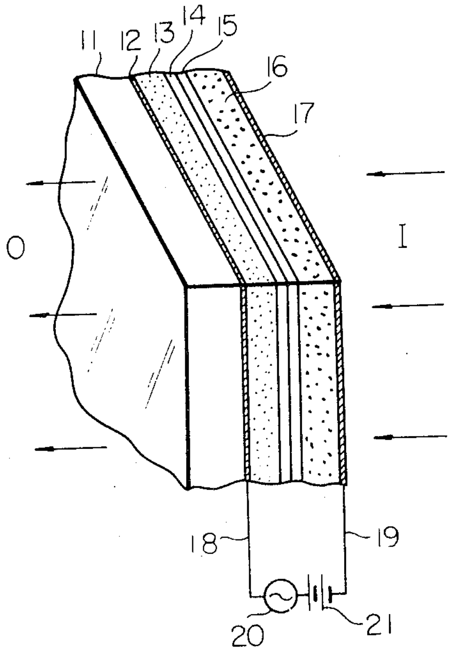

Fig. 1

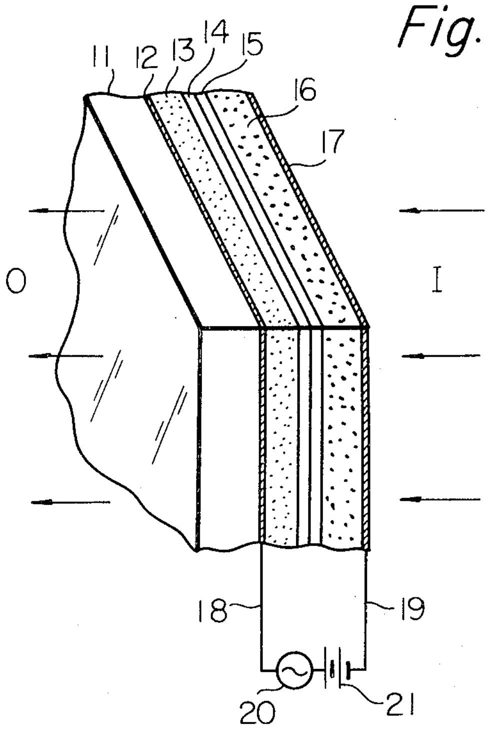

Fig. 2

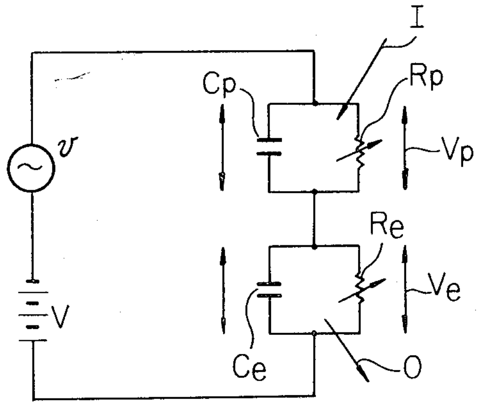

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Fig. 3

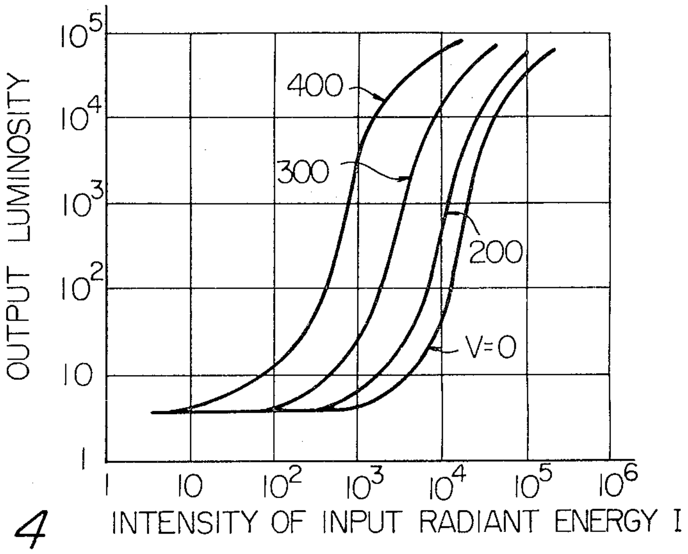


Fig. 4

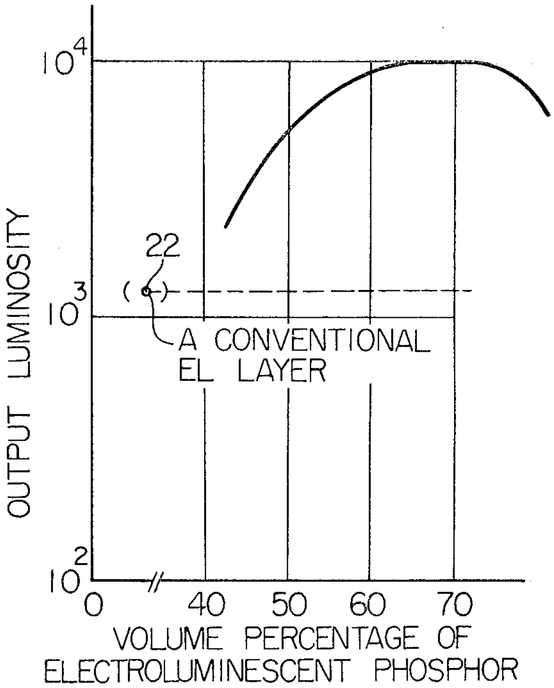
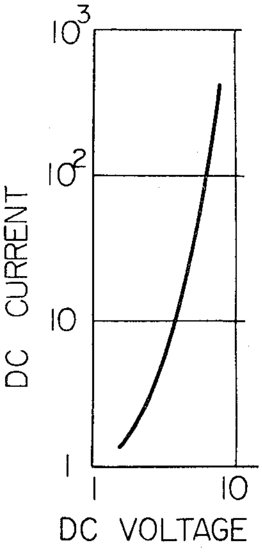


Fig. 5



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SOLID-STATE IMAGE INTENSIFIER

This invention relates to a solid-state image intensifier including an electroluminescent layer and a photoconductive layer as elements thereof. More particularly, the invention relates to such image intensifers which are adapted for use as amplifiers of radiant energy or as converters of invisible radiation into visible radiation.

In the known solid-state image intensifiers comprising an electroluminescent phosphor and a photoconductor, the electroluminescence is controlled by an AC field in response to changes in the impedance of the photoconductor caused by radiant energy excitation. However, due to its geometric structure the photoconductor has a predominantly capacitive AC impedance in the dark or in a low input energy state, resulting in a low photoconductive sensitivity. This imposes a limitation on the operating range of the image intensifier to high input energy range.

It is, therefore, an object of this invention to provide a new and improved solid-state image intensifier having a wide operational range including the low input energy range.

It is another object of this invention to provide a solid-state image intensifier which includes an electroluminescent layer having a nonlinear resistance and which is operated by AC and DC voltages.

It is a further object of this invention to provide a solid-state image intensifer in which a unidirectional voltage applied thereto is varied to shift the characteristic curve to the low input energy range without appreciable changes in contrast ratio and gamma value.

It is yet a further object of this invention to provide a solid-state image intensifier having an increased output luminosity and an improved resolution and which is easy to manufacture.

These and other objects of this invention will be apparent from the following description when taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a schematic sectional view of a solid-state image intensifer according to this invention;

FIG. 2 is an equivalent circuit of the image intensifier shown in FIG. 1;

FIG. 3 is a plot of output luminosity against intensity of input radiant energy for the solid-state image intensifier of FIG. 1;

FIG. 4 is a plot of output luminosity against volume percentage of electroluminescent phosphor in an electroluminescent layer; and

FIG. 5 is a voltage-current characteristic of the electroluminescent layer.

Referring now to the drawings and in particular to FIG. 1, there is illustrated a fragmentary sectional view of a solid-state image intensifier or light amplifier constructed in accordance with this invention. In the figure, reference numeral **11** designates a transparent support member or glass plate by which is coextensively supported a transparent conductive film **12**. The transparent conductive film **12** is used as a first electrode and may comprise metal oxides such as tin oxide. A layer of electroluminescent material **13** is formed on the transparent conductive film **12**. The electroluminescent material may be constituted of particles of electroluminescent phosphor embedded in a dielectric material and having the property of emitting light under the influence of an AC electric field. It may comprise, for example, zinc sulphide activated with copper and aluminum and mixed with a suitable plastic such as epoxy resin. Alternatively, an electroluminescent layer **13** comprised of phosphor mixed with a vitreous enamel such as boro-silicate glass enamel may be used. The electroluminescent layer **13** is approximately fifty microns thick and has a nonlinear resistive impedance. It has been found that 45 to 70 percent by volume of the electroluminescent phosphor provides a proper non-linear resistance. The nonlinear resistance of the electroluminescent phosphor itself is utilized to accomplish this invention. If the volume percentage is below 45 percent, the particles of electroluminescent phosphor are insulated from each other by means of their surrounding binding material. With the percentage about 70 percent, the electroluminescent layer **13** is porous, having so low a mechanical strength that it is impossible to machine the layer. Further, the layer **13** represents a saturation in its luminosity with reduced light output.

In our experiments, the boro-silicate glass enamel is, for example, a compound containing, by weight percentages, SiO_2 14.5 to 44.1%, B_2O_3 23.7 to 28.7%, ZnO 2.2 to 23.5%, BaO up to 14.6%, Na_2O 10.9 to 15.4%, K_2O up to 4.2%, TiO_2 up to 9.0%, Al_2O_3 up to 2.7%, and CaO, MgO, Fe_2O_3 and PbO up to 1.2%, and having a softening point of 45° to 515°C and a volumetric thermal expansion coefficient of 260×10^{-7} to 340×10^{-7}/°C. The boro-silicate glass enamel described above yields especially good results. In this case, a heat resisting substrate, for example, such as soda glass plate which has a higher softening point than that of the boro-silicate glass enamel and substantially same volumetric thermal expansion coefficient thereof is used as the transparent support member. The soda glass has a softening point of 690°C and a volumetric thermal expansion coefficient of 310×10^{-7}. The electroluminescent phosphor powder is mixed with the boro-silicate glass enamel powder by the volume percentage mentioned above and with an organic solvent such as alcohol. The mixture is applied in proper thickness on the surface of the transparent conducting layer, which is heated at a certain temperature. The temperature is higher than the softening point of the glass enamel material but lower than that of the transparent support member. For example, the temperature may range from 500° to 670°C. Thus, the electroluminescent layer is formed on the transparent conducting layer.

Deposited upon and in contact over an extended area with the electroluminescent layer **13** is a resistive light-reflecting layer **14** comprising particles of light-reflecting ferroelectric material such as $BaTiO_3$ mixed with a resistive plastic. Instead of the resistive plastic, a suitable plastic such as epoxy resin mixed with a resistive material such as TiO_2 may be used. This layer **14** is approximately 10 microns thick.

Deposited upon and in contact over an extended area with the resistive light-reflecting layer **14** is a resistive light opaque layer **15** which may comprise a powdered resistive material such as CdS:Cl. This layer **15** is approximately 10 microns thick. One function of these resistive layers **14** and **15** is to prevent the non-linearly resistive electroluminescent layer **13** from being damaged as a result of dielectric breakdown by a DC voltage as applied thereto. Correction of the resistance of the electroluminescent layer **13** as well as impedance matching of the DC circuit is provided by the resistive layers **14** and **15**. It should be noted in this connection that since the ferroelectric material such as $BaTiO_3$ provides an increased mean dielectric constant for the resistive light-reflecting layer **14**, the electroluminescent layer **13** is effectively energized by alternating voltages with reduced AC voltage loss. Further, since the ferroelectric material has a high specific resistance, the resistance of the light-reflecting layer **14** can be easily controlled by adjusting the amount of the material mixed with the binder. On the other hand, since the light-opaque layer **15** comprises a powdered resistive material, it is very easy to control the resistance of the layer by adjusting the amount of the resistive material mixed. The resistances of the two intermediate layers **14** and **15** may be linear or nonlinear. It is preferable that, when a DC voltage applied across the solid-state image intensifier, the resistances of the intermediate layers are at least smaller than the dark resistance of the photoconductive layer.

Deposited upon and in contact over an extended area with the resistive light opaque layer **15** is a photoconducting layer **16** having a thickness ranging from approximately 200 to 500 microns. The material of this photoconducting layer **16** may, for example, comprise cadmium sulfide, cadmium selenide or cadmium sulfo-selenide activated by copper, silver, chlorine, aluminum or gallium. More generally the photoconductive layer **16** may, for example, comprises the sulfides, selenides, or telurides, of cadmium, lead, or zinc, or may be any other known photoconductor mixed with a suitable plastic binder. The photoconductive layer **16** has its impedance varied under the influence of radiations, such as light, X-rays, infrared rays or ultraviolet rays.

Finally, upon the photoconducting layer **16**, there is deposited in contact over an extended area therewith a second conducting electrode **17** which may be a conducting layer of metal oxides such as tin oxide (SnO_2) or a film formed by evaporating a metal such as aluminum on the photoconductive layer **16**. Alternatively, an electrode consisting of a plurality of wires arranged in uniformly spaced parallel relationship, or an apertured or grid-like electrode may be used. The second conducting electrode **17** is permeable to an input energy signal I in the form of visible light, X-rays, infrared rays or ultraviolet rays. Electrical contact is made with both of the conducting electrodes **12** and **17** so that lead wires **18** and **19** may be brought out from these electrodes **12** and **17**, respectively. Connected between these lead wires **18** and **19** are a source **20** of alternating current in series with a source **21** of direct current. The voltage of the DC voltage source **21** may be varied as desired. The connections of the DC voltage source **21** is so selected that the positive pole thereof is connected to the first conducting electrode **12** through the source **20** and the negative pole thereof is connected to the second conducting electrode **17**.

Turning now to FIG. 2, there is shown an equivalent circuit of the solid-state image intensifier shown in FIG. 1. The solid-state image intensifier is capable of reproducing a positive output image O which is a replica of the image incident thereon. In the figure, reference character R_p designates a resistance of the photoconductive layer **16**. The resistance R_p varies in response to radiant energy excitation. In parallel with resistance R_p is a capacitance C_p of the photoconductive layer **16**. An arrow is used to indicate the input radiant energy I falling upon the photoconductive layer **16**. A parallel combination of a resistance R_e and a capacitance C_e, which correspond to the resistance and capacitance of the electroluminescent layer **13**, respectively, is connected to the parallel combination of the resistance R_p and the capacitance C_p. The resistance R_e is nonlinearly variable as a function of DC voltage applied across the electroluminescent layer **13**. The range over which the resistance R_e varies is appropriately larger than the range over which the resistance R_p varies in response to radiant energy excitation. Another arrow is used to indicate the reproduced image output O.

As shown, a unidirectional voltage or DC voltage of varying magnitudes and an AC voltage are connected in series between the serially connected two parallel combinations of resistors and capacitors. When the DC supply voltage is adjusted to be zero, the DC voltage V_e is zero, thus increasing the nonlinear resistance R_e to an extremely large value. Consequently, the AC impedance of the electroluminescent layer **13** is predominantly capacitive such as a conventional photoconductive layer. The DC voltage V_p across the photoconductive layer is also zero, resulting in the image intensifier having substantially no sensitivity in the range of low input energy such as conventional image intensifiers of AC operation.

When the magnitude of the DC voltage is increased, a DC voltage V_p is applied across the photoconductive layer **16**, the DC voltage V_p being determined by the ratio of R_p to R_e. Under such conditions, when the input energy I is increased from low to high energy level, the resistance R_p decreases, with the resultant decrease in the voltage V_p. This invites an increase in the voltage V_e, which, however, causes a reduction in the nonlinear resistance R_e. Thus, there occurs substantially no change in the ratio of R_p to R_e. It is to be understood that the voltage V_p as applied across the photoconductive layer is kept at a substantially constant value by the action of the voltage-controlled nonlinear resistance R_e.

It is well known in the art that the photoconductive sensitivity of a photoconductive powder layer when operated by an AC voltage increases with the increase of a DC voltage superimposed thereon. As mentioned above, since the photoconductive layer **16** of the present solid-state image intensifer has a relatively large DC voltage V_p to be superimposed on an AC voltage applied across the photoconductive layer, the photoconductive sensitivity is greatly improved as compared to that measured when $V_p = 0$. This results in improvement of the overall sensitivity of the solid-state image intensifier against an input energy signal. According to this solid-state image intensifier, therefore, it is possible to obtain a sufficient luminosity with a relatively low input energy signal applied. With the DC supply voltage V increased, the characteristic curve of the image intensifier is continuously shifted to a lower input energy range without appreciable changes in contrast ratio and gamma value.

FIG. 3 is a plot of output luminosity of an input energy signal, in which various curves represent different values of the DC supply voltage V. The magnitude of the DC supply voltage V was varied from 0 to 400 volts, with the AC supply voltage V kept at 300 volts at a frequency of 1 KHz. A radiation of X-rays was employed as the input energy signal I. As will be seen from FIG. 3, the increase in the DC supply voltage V causes the characteristic curve to Shift to lower input energy side, without producing appreciable changes in contrast ratio and gamma value.

FIG. 4 is a plot of output luminosity against volume percentage of electroluminescent phosphor particles in the electroluminescent layer **13** when energized by a constant AC field. In the plot, the output luminosity of a conventional electroluminescent layer comprising 20 percent of electroluminescent phosphor and 20% of SnO_2 is indicated as at **22** by comparison. The SnO_2 has a good reflectivity to the luminous spectra of the electroluminescent layer and is employed as a resistive powder mixed with the electroluminescent phosphor. As will be apparent from the inspection of FIG. 4, according to this invention, the maximum output luminosity can be obtained with 70 percent of electroluminescent phosphor contained in the layer. In this instance, the electroluminescent phosphor is used itself as a non-linear resistive powder. In the conventional electroluminescent layer, it is necessary to have a resistive powder such as SnO_2 mixed with the electroluminescent phosphor in order to provide resistance to the electroluminescent layer. This leads to a reduction in the percentage of the electroluminescent phosphor in the mixture and consequently to a decrease in the output luminosity. Further, in manufacturing the layer there is a likelihood of particles of the electroluminescent phosphor being dispersed nonuniformly in the layer. However, since, as described above, the electroluminescent layer according to this invention contains substantially no additional resistive powder as a material imparting resistance to the electroluminescent layer, it has an increased output luminosity and is easier to manufacture. Moreover, the present solid-state image intensifier has an improved resolution because of its sandwiched structure.

FIG. 5 illustrates a nonlinear voltage-current characteristic of the electroluminescent layer containing 50 percent of electroluminescent phosphor. With the volume percentage of the electroluminescent phosphor varied from 45 to 70 percent, the electroluminescent layer varies its resistance over a range of two orders.

As has been described above, the invention provides a new and improved solid-state image intensifier having a wide range of operation, an increased output luminosity and an improved resolution and which is easy to manufacture.

What is claimed is:

1. A solid-state image intensifier comprising: a photoconductive layer the AC impedance of which is varied in response to radiant energy; said photoconductive layer including a photoconductive material selected from the group consisting of sulfides, selenides and telurides of cadmium, lead and zinc; an electroluminescent layer deposited upon and in contact over an extended area with said photoconductive layer for emitting light in response to an electric field applied thereto; said electroluminescent layer consisting of 45 to 70 percent by volume of zinc sulfide particles mixed with a binding material and having an inherent nonlinear resistance which functions to keep a DC voltage applied across said photoconductive layer at a substantially constant value; a conductive layer disposed on said photoconductive layer and permeable to the input radiation, said input radiation being one of the form of visible light, X-rays, infrared rays or ultraviolet rays; a transparent conducting layer disposed on said electroluminescent layer; and DC and AC voltage sources connected in series between said conductive and conducting layers.

2. A solid-state image intensifier according to claim 1, in which said zinc sulfide is activated with copper and aluminum.

3. A solid-state image intensifier according to claim 1, in which said binding material selected from the group consisting of a vitreous material such as boro-silicate glass enamel and a plastic such as epoxy resin.

4. A solid-state image intensifier according to claim 1, in which continuous layers of a resistive and light-reflective material and a resistive light-opaque material are interposed between said photoconductive layer and said electroluminescent layer.

5. A solid-state image intensifier according to claim 4, in which said light-reflective layer comprises particles of ferroelectric material such as $BaTiO_3$ mixed with a resistive plastic.

6. A solid-state image intensifier according to claim 4, in which said light-reflective layer comprises particles of ferroelectric material such as $BaTiO_3$ mixed with a resistive material such as TiO_2 and a plastic such as epoxy resin.

7. A solid-state image intensifier according to claim 4, in which said light opaque layer comprises a powdered resistive material such as CdS:Cl.

8. A solid-state image intensifier according to claim 1, in which the connections of said DC voltage source are selected that the positive pole thereof is connected to said electroluminescent layer side and the negative pole thereof is connected to said photoconductive layer side.

9. A solid-state image intensifer according to claim 1, in which a unidirectional field provided by said DC voltage source is varied to shift the characteristic curve to low input energy range without any appreciable change in contrast ratio and gamma value.

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