May 22, 1956 E. E. SHELDON 2,747,132

DEVICE SENSITIVE TO INVISIBLE IMAGES

Filed Dec. 18, 1951 2 Sheets-Sheet 1

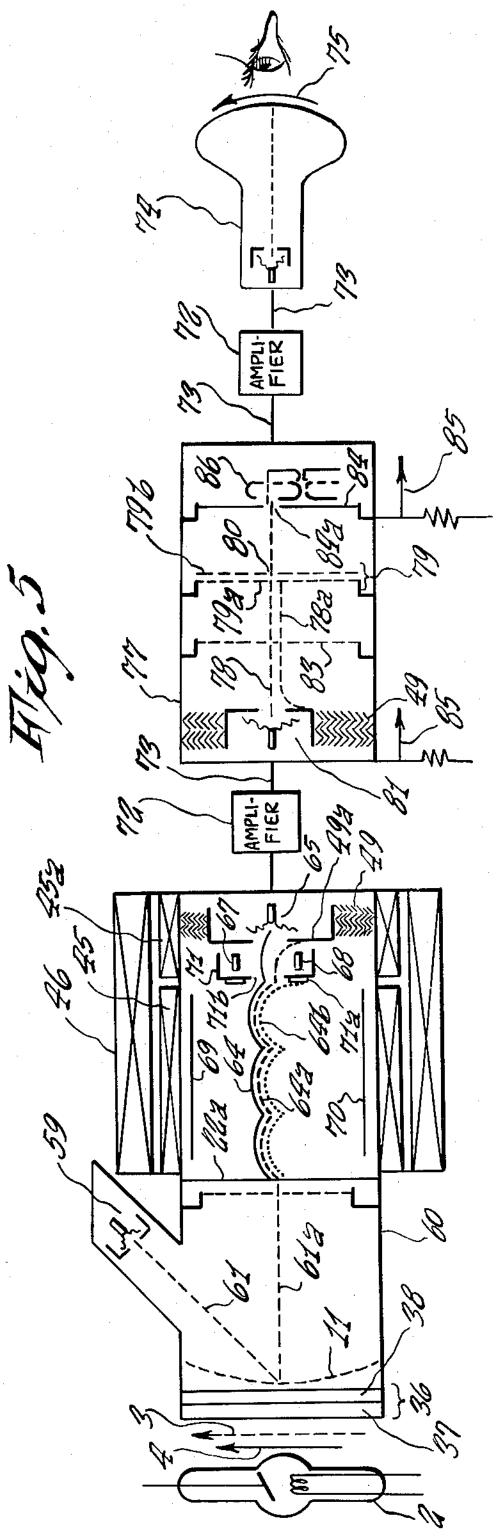



Fig. 5

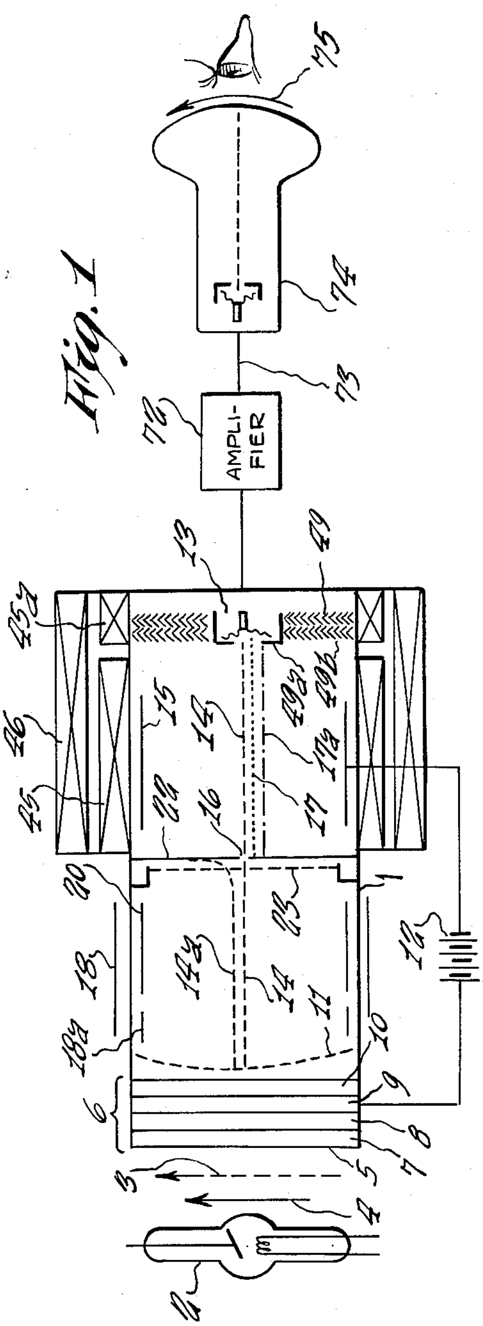



Fig. 1

INVENTOR:
EDWARD EMANUEL SHELDON.
BY: Julian J. Wittal,
HIS ATTORNEY

DEVICE SENSITIVE TO INVISIBLE IMAGES

Filed Dec. 18, 1951 2 Sheets-Sheet 2

Fig. 2

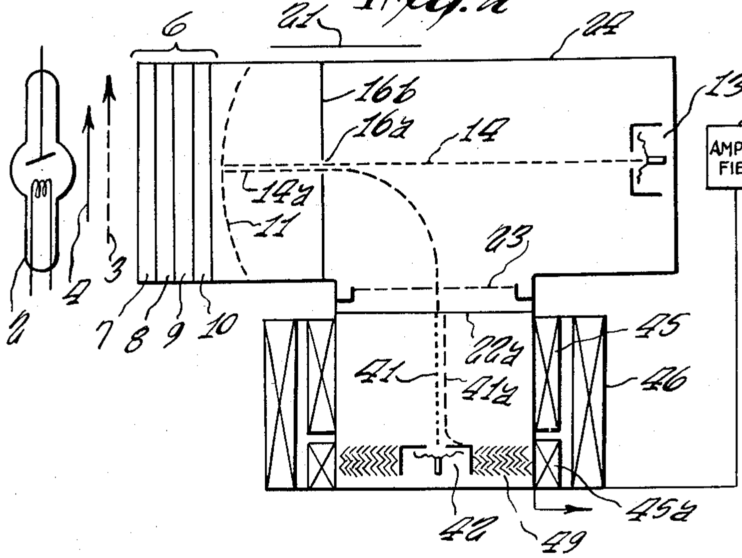



Fig. 1a

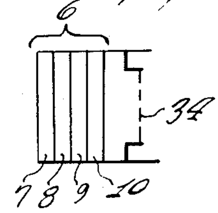


Fig. 1b

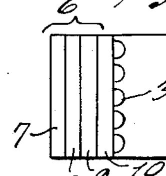


Fig. 3

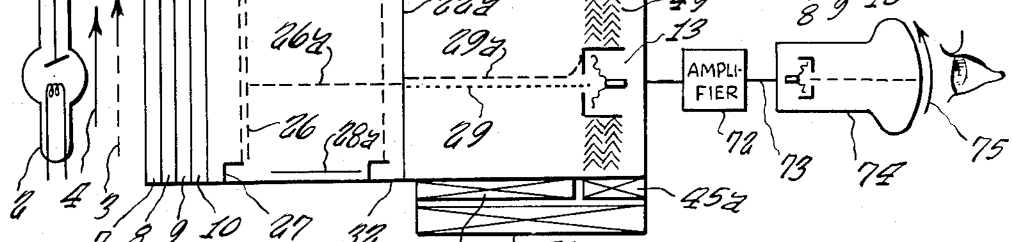
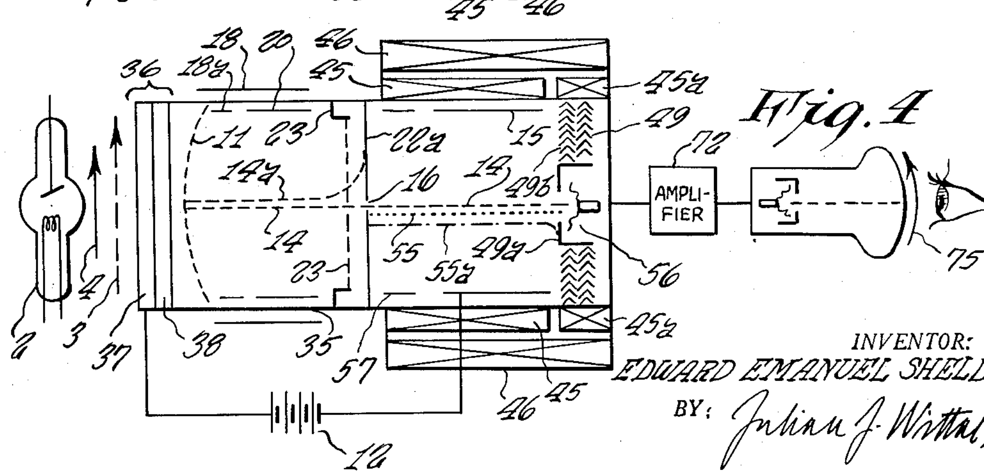



Fig. 4




INVENTOR:
EDWARD EMANUEL SHELDON
BY: Julian J. Wittal,
HIS ATTORNEY

United States Patent Office

2,747,132
Patented May 22, 1956



2,747,132

# DEVICE SENSITIVE TO INVISIBLE IMAGES

Edward Emanuel Sheldon, New York, N. Y.

Application December 18, 1951, Serial No. 262,223
15 Claims. (Cl. 315—11)

This invention relates to an improved method and device for intensifying images and refers more particularly to an improved method and device for intensifying images formed by the X-ray radiation, which term is meant to include other invisible radiations, such as gamma rays and the like, and also irradiation by beams of atom particles, such as e. g. neutrons, and is for the same subject matter as my U. S. Patent No. 2,555,424.

The main problem in using X-rays or neutrons for medical diagnosis is the danger of causing damage to the patient by radiation. The danger of over-exposure necessitates the use of a very weak X-ray or neutron beam, which means that the X-ray intensity must be very low and, therefore, we do not have enough of X-ray quanta in the invisible X-ray image of the human body. If we do not use all X-ray quanta, we will not be able to reproduce an image having all the necessary intelligence, no matter how much we will subsequently intensify this image by electronic means. The present X-ray receivers of photoemissive type have a very low quantum efficiency, such as the order of a fraction of 1% and, therefore, suffer from this basic limitation. The solution of this problem and primary objective of my invention is to provide an invisible radiation receptor, which will utilize all incoming photons of radiation, which means it will have a quantum efficiency close to unity.

Another object of this invention is to provide a method and device to produce intensified images. This intensification will enable the overcoming of the inefficiency of the present X-ray fluoroscopic examination. At the present level of illumination of the fluoroscopic image, the human eye has to rely exclusively on scotopic (dark adaptation) vision, which is characterized by a tremendous loss of normal visual acuity in reference both to detail and to the contrast. Without intensification of luminosity of at least of the order of 1000, the eye is confined to so-called scotopic vision, at which it is not able to perceive definition and contrast of the fluoroscopic image. It is well known that intensification of the brightness of the X-ray fluoroscopic image cannot be achieved by increase of energy of the X-ray radiation, as it will result in damage to the patient's tissues. Therefore, to obtain the objects of this invention, a special X-ray sensitive pick-up tube and system had to be designed.

Another object of this invention is to make it possible to prolong the fluoroscopic examination since it will reduce markedly the total strength of radiation affecting the patient's body. Conversely, the exposure time or energy necessary for the radiography may be reduced.

Another object is to provide a method and device to produce sharper X-ray fluoroscopic and radiographic images than was possible until now.

Another important objective of this invention to provide a method and device to amplify the contrast of the X-ray image.

The objectives of this invention were obtained by a novel invisible radiation sensitive television system. This system consists of an invisible radiation source, a novel



invisible radiation sensitive pick-up tube, amplifiers and receivers for reproducing said invisible image. The novel pick-up tube has X-ray or neutron sensitive composite screen, which consists of a fluorescent layer, a conducting separating layer and a photoconductive layer. The photoconductive layer is a dielectric, which becomes electrically conductive when irradiated by light. The invisible X-ray or neutron image produces, therefore, in the invisible radiation sensitive screen a fluorescent light image. The fluorescent light acts on a photoconductive layer and creates therein a pattern of electrical conductivity changes, as well as a pattern of electrical potentials on the surface of said conductive layer. The latter process has a high quantum efficiency such as approaching unity. The electrical conductivity changes and the electrical potentials on the surface of the conductive layer have the pattern of the X-ray or neutron image. They cannot, however, be used directly for reproduction of a visible image with the necessary intensification. They are used in my invention to modulate a strong uncontrolled electron beam. The modulated electron beam will have, therefore, the pattern of the original X-ray or neutron image. This electron beam when returning can be accelerated, electronoptically diminished and converted into video signals which are used to reproduce a visible image with necessary intensification.

In another modification of my invention, the novel invisible radiation sensitive image tube has X-ray or neutron receiving screen only of a dielectric material, which exhibits property of becoming conductive directly in response to X-ray or neutron beams. The invisible X-ray or neutron image produces within said invisible radiation sensitive screen a pattern of electrical conductivity changes and on the surface of said screen a pattern of electrical potentials with a high quantum efficiency, such as approaching unity. The electrical conductivity changes and potentials have the pattern of the X-ray or neutron image. The theory and explanation of this phenomenon is given by the article of S. G. Zizzo and J. B. Platt "Detection of X-ray quanta by a cadmium-sulphide crystal counter," Physical Review, volume 75, September 1, 1949, page 704. It is believed that energetic X-ray photons striking X-ray sensitive dielectric materials are able to remove an electron from its place in the matter. The deficiency of an electron can be considered as a positive particle, which is also called a positive hole. Electrons and positive holes move across said insulator under the influence of electrical field applied by means of conducting electrodes, which are deposited on either side of insulator. The electrons and positive holes, therefore, produce within the invisible radiation sensitive screen, a pattern of electrical charges and of electrical conductivity changes with a high quantum efficiency such as approaching unity. At the same time, a pattern of electrical potentials is formed on the surface of invisible radiation sensitive screen. The electrical charges, the conductivity changes, as well as potentials pattern have the pattern of the X-ray or neutron image. They cannot, however, be used directly for reproduction of a visible image with the necessary intensification. In my invention they are used to modulate an electron beam, which irradiates this electrical pattern on said screen. The modulated electron beam will have, therefore, the pattern of the original X-ray or neutron image. This electron beam is converted into video signals. Video signals are sent to amplifiers. By the use of variable mu amplifiers in one or two stages, intensification of video signals can be produced in non-linear manner, so that small differences in intensity of succeeding video signals can be increased one to ten times, producing thereby a corresponding gain of the contrast of the final visible image in receivers, which was one of the objectives of this invention. Amplified video signals are transmitted to kinescopes to reproduce a visible image with necessary intensification, as was explained in my U. S. Patent No. 2,555,424.

In some cases, it may be necessary to include a special storage tube in the invisible radiation image intensifying system, in order to overcome the flicker resulting from too long a frame time. In such case, video signals are sent to the storage tube having a special storage target and are deposited there by means of modulating electron scanning beam of said storage tube. The stored electrical charges having the pattern of X-ray image, are released from said electrode, after predetermined time, by scanning it with another electron beam or, in a modification of the storage target having photoemissive elements, by irradiating it with light. The released electron image is converted again into video signals and sent to final receivers to produce invisible image with desired intensification and gain in contrast and sharpness.

In this way, all purposes of the invention were accomplished. The invisible X-ray image is converted into video signals without any loss of information because of quantum efficiency of the X-ray sensitive layer and the resulting video signals are intensified to give the necessary brightness of reproduced X-ray image.

It is obvious that my invention is not limited to ionizing radiations such as X-rays or neutrons, but it may also be used for other invisible radiations, such as infrared or ultra-violet.

The invention will appear more clearly from the following detailed description when taken in connection with the accompanying drawings by way of example only preferred embodiments of the inventive idea.

In the drawings:

Figure 1 is a cross-sectional view of the invisible radiation image intensifying system.

Figures 1*a* and 1*b* are front views of the modification of the photocathode in the pick-up tube.

Figure 2 is a cross-sectional view of the X-ray or neutron intensifying system showing a modification of the pick-up tube having two electron guns.

Figure 3 is a cross-sectional view of the invisible radiation intensifying system showing a modification of the pick-up tube.

Figure 4 is a cross-sectional view of a modification of the invisible radiation sensitive pick-up tube.

Figure 5 is a cross-sectional view of the image intensifying system showing the use of a storage tube.

Reference will now be made to Fig. 1, which illustrates the novel X-ray or neutron sensitive image tube **1**. The X-ray source **2** produces an invisible image **3** of the examined body **4**. The invisible image passes through the face **5** of the tube, which obviously must be of material transparent to the radiation used and may be flat or convex in shape, and strikes the composite photocathode **6** disposed inside of the image tube. The composite photocathode **6** consists of an invisible radiation transparent, light reflecting layer **7**, a fluorescent layer **8** sensitive to said invisible radiation, a very thin conducting layer **9** and a photoconductive layer **10**. The layer **7** may be of aluminum, gold, silver or platinum and must be very thin in order not to absorb the invisible image. In case the pick-up tube **1** is used for intensification of infra-red or ultra-violet images, the layer **7** may be omitted. Layer **8** may be made of various sulphides, selenides, silicates, organic phosphors, such as stilbene, anthracene, tungstates, ZnO or $BaPbSO_4$. For neutron images, the fluorescent layer should be activated with elements which have a large cross-section for neutrons, such as boron, lithium, gadolinium or an additional neutron sensitive layer, such as of boron, lithium or gadolinium, should be disposed adjacent to the fluorescent layer.

The fluorescent layer for infra-red images should be preferably of sulphides or selenides activated by cerium, samarium or europium. Infra-red sensive phosphors exhibit a considerable lag. Therefore, care should be exercised to select a phosphor with a short after-glow.



Conducting layer **9** must be transparent to fluorescent light and must be exceedingly thin in order not to impair resolution of the image. I found that the maximum thickness of the conducting layer, which separates fluorescent and photoconductive layers must be less than 0.25 millimeter in order to reproduce an image of diagnostic value. The conducting layer may be of gold, silver, platinum, or may be of material such as plastic, glass or mica, coated with the conductive layer, such as known under the trade name "Nesa" and manufactured by Pittsburgh Glass Company. The photoconductive layer **10** may be of CdS, $Sb_2S_3$, selenium or ZnSe. Many sulphides, selenides, iodides, arsenides and oxides exhibit photoconductive effect and may be used for the purposes of my invention. It is to be understood, however, that my invention is not limited to any particular material as there are many substances which have such properties and are known in the art. The invisible X-ray or neutron image produces in the fluorescent layer **8** a fluorescent light image having the pattern of said invisible image. The fluorescent image produces within the photoconductive layer a pattern of changes in electrical conductivity and on the surface of said photoconductive layer a pattern of potentials according to the pattern of said fluorescent light image. The photoconductive layer **10** is under the influence of an electrical field produced by an extrinsic source of electrical power, such as battery **12**, which is connected to the conducting layer **9**. Under the influence of this electrical field, the electrons and positive holes liberated in the photoconductive layer by the impingement of fluorescent light from the layer **8**, and in some cases also of the X-ray or neutron image, move to respective electrodes. Therefore, the pattern of potentials having the pattern of the original X-ray or neutron image appears on the uncovered surface of the photoconductive layer **10**. In some cases, better results are obtained by using a pulsating electrical field instead of a battery. In particular, applying a square wave voltage of a low frequency, such as 15–30 cycles per second to the conducting layer **9** will markedly improve the sensitivity of the photocathode and will prevent "fatigue" effects.

The uncovered surface of layer **10** is irradiated by a broad beam **14** of electrons from the electron gun **13**. The broad electron beam is focused by magnetic or electrostatic fields **15** to a small diameter, so that it will pass through the aperture **16** in the target **22**, such as of mica, silica or glass. The electron beam **14**, after passage through aperture **16**, is enlarged by suitable magnetic or electrostatic fields **18** to the size corresponding to the size of the photocathode. The electron beam **14**, when approaching photocathode, may have velocity of a few hundred volts. It is preferable, however, to use a slow electron beam. In such event, the electron beam **14** is decelerated in front of the photocathode by an additional decelerating electrode **18*a***, which may be in the form of a ring or of a mesh screen. The electron beam approaching the photoconductive layer **10** is modulated by the pattern of potentials on its surface and of conductivity changes within said layer. The electrons of the beam which strike conducting areas of the photoconductive layer **10** reach conducting layer **9** and are led away. The electrons of the electron beam, which find non-conductive parts of the layer **10**, cannot pass through. In addition to said modulation of the electron beam **14** by conductivity changes, it is also modulated by the pattern of potentials on the surface of the photoconductive layer **10**. The areas of a higher negative potential will reflect electrons more than areas having a lower potential acting as an electron mirror **11**. The reverse situation exists if the X-ray induced conductivity is due to positive holes, because in such a case the areas of higher positive potential will obviously attract electrons instead of repelling them.

By proper choice of material for photoconductive layer, these two modulating effects can be made to work in the same direction and improve modulation of the electron beam. The returning electron beam **14a** is, therefore, modulated by the photoconductive image and potential image in the composite photocathode **6** and carries the image of the examined body. The returning electron image **14a** is now intensified by acceleration. This is accomplished by accelerating fields or electrodes **20**, which are well known in the art and, therefore, it is believed, they do not have to be described in detail.

Further intensification of the returning electron image may be obtained by its electron-optical diminution, which results in intensification proportional to the square power of linear decrease in size. The electron-optical demagnification is accomplished by magnetic or electrostatic fields and is well known in the art. The action of the electron beam **14** should last no longer than $\frac{1}{10}$ second. After this period, the electron gun **13** is inactivated for a very short time. Instead, the accelerating electrodes **20** and the electron-optical lenses for electron-optical diminution of the returning electron image **14a** are activated. The switching system for activating and inactivating electron gun and the electrical fields described above may be operated by thyratron or ignitron controlled timer and is not shown in detail because it is well known in the art and will only complicate the drawings.

The returning electron beam **14a** strikes the storage target **22** with velocity sufficient to produce secondary electron emission from the target **22** higher than unity. The secondary electrons are collected by the adjacent mesh screen **23** and are led away. As a result, a positive charge pattern remains in the semi-conductive target **22**. The target **22** may be of mica, silica or glass and must be very thin, such as from 5 to 100 microns. The positive charge image, because of thinness of target **22** can migrate to its opposite side in less than $\frac{1}{30}$ second. This time depends on resistivity of the target and may be selected as desired for purposes of invention. After the charge image has been built up in the storage target, the second phase of the operation begins. In this phase, the electron gun **13** is adjusted to produce a fine electron beam **17** to scan the target **22** in television-like raster. The electron beam **17** is focused by focusing magnetic or electro-static coil **45** and by the alignment coil **45a** which are well known in the art and, therefore, are not described in detail in order not to complicate the drawings. The electron beam **17** is deflected by deflecting coils **46** and scans the target in the usual television manner. The electron beam **17** is slowed down in front of the target **22** by decelerating electrode, which may be in the form of a ring or mesh screen. A high velocity electron beam may be used also in this invention. The slow electron beam **17** is modulated by the pattern of positive electrical charges on the target **22**. The returning electron beam **17a** carries, therefore, image information, is directed now to multipliers **49** and strikes the first stage **49a** of multiplier. The secondary electrons produced by impingement of electron beam **17a** are drawn to the next stage **49b** of the multiplier **49**, which is around and in the back of the first stage. This process is repeated in a few stages resulting in a marked multiplication of the original electron signals. The signal currents from the last stage of the multiplier are converted over a suitable resistor into video signals. Video signals are fed into television amplifiers **72** and then are sent by coaxial cable **73** or by high frequency waves to the receivers of kinescope type **74** or facsimile type, in which they are reconverted into visible images for inspection or recording. The synchronizing circuits are not shown as they are well known in the art and would only complicate drawings.

I found that modulation of electron beam **14** by the conductivity or the potential image occurs in a very short time, such as a few micro-seconds. It is possible, therefore, to intensify the charge image in storage target by irradiating photocathode **6** with electron beam **14** a few hundred or a few thousand times per second, instead of 15–30 times per second.



A very important feature of my novel X-ray or neutron sensitive image tube is that it can be operated as a storage tube. This means that after the invisible image is formed in the photocathode **6** as a pattern of electrical conductivity changes or of electrical potentials, X-ray or neutron radiation may be shut off and the image may be read for the desired time. This results in a great reduction of X-ray or neutron exposure of patients, which was one of the primary objectives of my invention. The operation of the image tube **1** or **24** as a storage tube is essentially the same as described above, except that X-ray or neutron radiation may be stopped after one short exposure. The storage effect of my image tube is due to photoconductive lag observed in insulators, such as selenium, cadmium sulphide or antimony trisulphide and others when the incident light is of a low intensity. Such conditions prevail in medical fluoroscopy where the brightness of fluorescent light image produced in layer **8** by X-ray or neutron image is in the range of 0.01–0.001 footcandle. The photoconductive lag means that conductivity pattern within the layer **10** and potential pattern on the uncovered surface of said photoconductive layer persists for many seconds. During all this time, the electron beam **14** can be modulated by said conductivity or potential pattern and will be building up a charge image corresponding to the original X-ray or neutron image in the storage target **22**. The photoconductive lag may be prolonged by refrigerating the photoconductive layer **10** of the photocathode, or by addition of suitable impurities, such as Cu when using CdS for a photoconductive layer.

Another important advantage of my X-ray or neutron sensitive tube resides in the efficiency of the photoconductive layer as compared with the previously used photoemissive layer. Whereas the best photoemissive materials have quantum efficiency of the order of 3 to 5%, the photoconductive layer **10** has quantum efficiency close to unity or even exceeding unity. The efficiency of photoconductive layer **10** can also be increased by providing a strong electrical field across it, which serves to move liberated electrons and positive holes across said layer.

In a modification of my invention shown in Fig. 1*a*, the potential pattern of the uncovered side of the photoconductive layer **10** is intensified by disposing in close proximity to said uncovered side, a mesh screen **34**, which is connected to one terminal of the battery **12**; the other terminal of the battery is connected to conducting layer **9**. In this way, a strong electrical field is produced across layer **10**. In another modification of my invention shown in Fig. 1*b*, instead of a mesh screen, a discontinuous mosaic **34a** of conducting particles, such as gold, platinum or silver is deposited on the uncovered side of the photoconductive layer **10** to provide the second terminal for battery **12** for producing a strong electrical field across layer **10**. The response of X-ray or neutron sensitive layer **8** may be increased by irradiation of said layer with a green light simultaneously with X-ray or neutron exposure. In some cases, the use of infra-red or ultraviolet is preferable.

The larger the dark resistance of the photoconductive layer, the larger will be the potential pattern on its surface for modulating the electron beam **14**. In order to obtain both high photosensitivity and high resistance, photoconductive layer **10** may be made of two adjacent layers, such as one of a photoconductive material highly responsive to fluorescent light from layer **8** and one of having high resistance for storage of charges liberated in the first layer. A suitable combination for such composite photoconductive screen is a thin layer of selenium deposited on the top of a thin layer of cadmium sulphide or of antimony trisulphide so that selenium remains uncovered on one side for exposure to the electron beam **14**.

Great improvement is sensitivity of X-ray or neutron pick-up tube was obtained in modification shown in Fig. 2. In this embodiment of invention, the operation of the tube **24** is characterized by two different periods. In the first period, the build-up of the conductivity and potential image is accomplished. For this purpose, the positive potential applied to the conducting layer **9** must be high in order to make all electrons of the electron beam **14** impinge on the photoconductive layer **10**. The electron beam **14** in this phase of operation should have a high internal resistance. After the build-up of the invisible conductivity and potential image is concluded, the "reading" period begins. In the "reading" period, the potential applied to the conducting layer **9** is lowered so that the photoconductive layer **10** will not attract any longer electrons of electron beam **14**. The electron beam **14** in this phase of operation is modulated by conductivity and potential image formed before in layer **9**, during the build-up period. This two-step method of operation may be applied for the tube **1** as well. The returning electron beam **14*a*** carries, therefore, image having the pattern of the original X-ray or neutron image. In order to facilitate switching on and off of the electron gun, two electron guns are provided in this embodiment of invention. The returning electron beam **14*a*** passes through the opening **16*a*** in the diaphragm **16*b*** is bent by suitable magnetic fields **21** and is projected on the storage target **22*a***, which has been described above. The returning electron image **14*a*** is stored in said target as a charge image. It is then scanned by electron beam **41** from the electron gun **42**. The electron beam **41** is slowed down in front of the storage target **22*a***. The rest of the operation of the tube **24** is the same as was described above for tube **1**. The electron beam **41*a*** returning, after scanning said stored charged image, is converted into video signals. Video signals are amplified and are transmitted to receivers to reproduce a visible intensified image. It is obvious that the electron guns **13** and **42** may be spaced in tube **24** in many different ways. For example, the electron gun **13** may be disposed at an angle to the photocathode **6**, in which case the storage target **22*a*** and the electron gun **42** may be placed in the axis of the tube opposite to the photocathode **6**.

In some cases, the diaphragm **16*b*** may be eliminated. In such event, the storage target **22*a*** is protected from stray electrons of the electron beam **14**, which may be reflected during the build-up period by inactivation of the magnetic field **21**.

The potential pattern on the uncovered side of the photoconductive layer **10** of the composite photocathode **6** may also be used for modulating photoemission from a photoemissive layer closely spaced to said photoconductive layer. This embodiment of my invention is shown in Fig. 3. The photoemissive layer **26** which may be of mosaic or continuous type, is deposited in image tube **32** on a supporting conducting mesh screen **27**. The photoemissive layer is irradiated by a strong uncontrolled source of light **28**. The photoemission from layer **26** depends on potentials to which it is subject. The potential image on the surface of layer **10** produced by X-ray or neutron image, because of its close proximity, exerts a powerful influence and can control, therefore, photoemission from said layer **26**. The more positive the potential pattern on the layer **10**, the more suppressed is the photoemission of electrons from layer **26**. Therefore, photoelectron beam **26*a*** emitted from layer **26** has the pattern corresponding to the potential pattern on the surface of layer **10**. The photoelectron beam **26*a***, after being modulated by potentials of layer **10**, is intensified by acceleration and electron-optical diminution produced by magnetic or electrostatic fields **28*a***. Next it is projected on the storage target **22*a*** to produce a charge image, as was explained above. The stored charge image is scanned by a slow electron beam **29**. The returning electron beam **29*a*** is converted into video signals. Video signals are reconverted into a visible image **75** in receiver **74**, as was explained above.

Further improvement of operation of my X-ray or neutron sensitive image tube may be obtained by a better conversion of invisible radiation into electrons and positive holes in the photocathode. The previously described photocathode **6** had a serious deficiency, namely, the conversion of X-ray or neutron image into fluorescent image in layer **8** had only 3% quantum efficiency. By using photocathode of a material, which responds directly to X-ray or neutron radiation with quantum efficiency of unity, a thirty-fold additional increase in sensitivity of my system for invisible radiation images was obtained. This embodiment of invention is shown in Fig. 4.

The X-ray or neutron image sensitive tube **35** has photocathode **36** consisting of invisible radiation transparent, electrically conducting layer **37**, such as of gold, silver or platinum and a dielectric layer **38**, which exhibits X-ray or neutron induced conductivity, such as of cadmium sulphide, either of non-luminescent type or luminescent variety, diamond, sulphur, silver halides, antimony compounds, NaI(Tl) and others. The electrical field across layer **38** is provided by the source of electrical power, such as battery **12**, or a pulsating square wave voltage may be applied, as was explained above.

One terminal of the battery is connected to layer **37**, another terminal to the conducting coating inside of the tube. An improvement in operation of electrical field across the layer **38** may be obtained by using as a second terminal for the battery **12**, an additional mesh screen **34** in close spacing to layer **38**, as shown in Fig. 1*a*. Also, the arrangement shown in Fig. 1*b*, where a discontinuous mosaic of conducting particles, such as gold, platinum or silver, was applied as an electrode for the second terminal of battery, may be used for this purpose. The impingement of the X-ray or neutron beam on the layer **38** produces therein two different effects, a pattern of electrical conductivity changes within the layer and a pattern of potentials on its surface, both of which correspond to the original invisible image. By proper choice of X-ray or neutron sensitive material, these two effects may be made to work in the same direction and improve modulation of the irradiating electron beam.

It is obvious that photocathode **38** may also be used in the tube **1**, illustrated in Fig. 1, in the tube **24** shown in Fig. 2, or in the tube **32**, illustrated in Fig. 3.

The rest of the operation of X-ray or neutron sensitive pick-up tube **35** is the same as was described above for the tube **1** or **24**. The photocathode **36** is irradiated by a broad beam of electrons **14** from the electron gun **56**. The electron beam **14** is modulated by the pattern of conductivity and of potentials **11** of the layer **38**. The returning electron beam **14*a*** carries, therefore, image information. On its return, it is intensified by acceleration and electron-optical diminution, as was explained above. Next, it is projected on the storage target **22*a*** to be stored there, as a charge image.

After the X-ray or neutron image has been stored in the target **22*a***, the second phase of operation begins. In this phase, the electron gun **56** is adjusted to produce a fine electron beam **55** for scanning said target **22*a***. The scanning electron beam **55** produced by electron gun **56** is decelerated in front of the target **22*a*** by a ring electrode **57**. Also, a mesh screen may be used for this purpose. A high velocity scanning electron beam can be used in a modification of my invention as well. The electron beam **55** is focused by focusing electrostatic or electromagnetic coil **45** and by the alignment coil **45*a***, which are well known in the art and, therefore, are not described in detail in order not to complicate drawings. The electron beam **55** is deflected by deflecting coils **46** and scans the target **22a** in the usual television manner. The scanning electron beam neutralizes the positive charges produced in target **22a** by electron beam **14a**. Therefore, the scanning beam **55a**, which returns to the electron gun **56**, is modulated by the pattern of said charges and carries video information. This novel arrangement makes it possible to obtain much better results than the previously known systems, because the quantum efficiency of the novel photocathode **36** approaches unity, whereas the best quantum efficiency of fluorescent materials in combination with photoemissive materials is only a fraction of 1%. The returning electron beam **55a** strikes the first stage **49a** of the electron multiplier **49**. The secondary electrons from the first stage of the multiplier strike the succeeding stage **49b** around and in the back of the first stage. This process is repeated in a few stages, resulting in a marked multiplication of the original electron signals. The signal currents from the last stage of the multiplier are converted over a suitable resistor into video signals and are fed into television amplifiers **72**. Video signals, after amplification, are sent by coaxial cable **73** or by high frequency waves to the receivers of kinescope type **74**, facsimile or skiatron type, in which they are reconverted into a visible image **75** for inspection or for recording. In order to obtain amplification of contrast of the X-ray image, the amplifiers **72** are provided with variable mu tubes in one or two stages. Small differences in intensity of the succeeding video signals are increased by variable mu tubes in non-linear manner, resulting in a gain of the contrast of the visible image in receivers. The synchronizing circuits are not shown, as they are well known in the art and would complicate drawings.

The sensitivity of my device can be increased by irradiating the photocathode **38** with electron beam **14** in two steps, as was explained above. In the first period, the build-up of conductivity and potential image is accomplished. In the second period, said image is read by said electron beam **14** and stored in target **22a**.

The response of photocathode **36** may be increased by irradiating X-ray sensitive layer **38**, if it is of cadmium sulphide with green light. Also, addition of activators, such as Ag, increases sensitivity of CdS. Some cadmium sulphide crystals respond better to infra-red stimulation, some, on the contrary, lose their sensitivity when irradiated by infra-red light. If the X-ray sensitive layer is of diamond, the irradiation with infra-red light or with ultra-violet light will increase its sensitivity. Some X-ray or neutron sensitive materials have the best sensitivity when refrigerated. For example, silver chloride must be kept at the temperature of liquid air to be responsive to X-rays. Diamond performs well at room temperature; however, a marked increase of its sensitivity is observed when it is kept at the temperature of 200° K. Also, sensitivity of CdS increased markedly on cooling.

Some X-ray sensitive materials show a considerable lag, i. e., persistence of conductivity, after being irradiated by X-ray or neutron image. This lag effect may be used to operate image tube **36** as a storage tube. The conductivity lag means that conductivity pattern in the layer **38** and potential pattern on the uncovered surface of said layer **38** will persist for many seconds after the exciting X-ray or neutron radiation has been stopped. During all this time, the beam **14** will be modulated by said pattern and will continuously produce a charge image corresponding to the original X-ray or neutron image in the storage target **22a**. I discovered that repeated irradiation with electron beam does not discharge conductivity or potential pattern stored in layer **38**. Therefore, reproduced image can be read for a long time without maintaining X-ray or neutron radiation. This results in a large reduction of the total X-ray or neutron exposure affecting the patient. The pick-up tubes **1**, **24** or **35** may also serve for storage of images in a different manner. If the energy of the scanning electron beam is selected so that it is not sufficiently strong to neutralize the electrical charges in the storage target **22** or **22a** in one scan, then the stored image will persist for a long time. By proper selection of intensity of the scanning beam and of the capacity and resistance of storage target, the charge image can be stored and read in said target for many seconds. In such case, the target should be of material having high resistance, such as precipitated silicon, $CaF_2$, $BaF_2$, glass or mica.

Addition of suitable impurities, i. e. activators to the X-ray or neutron sensitive layer will markedly change its conductivity lag and time necessary to arrive at equilibrium. Also, changes of temperature have similar effects. In particular, the conductivity lag may be prolonged by refrigerating the layer **38** of the photocathode.

My invention can also be used for intensification of infra-red images. In such case, the invisible radiation sensitive layer **38** should be made of tellurides, sulphides, selenides or antimonides; especially their lead, thallium or magnesium compounds are very sensitive to infra-red radiation. Also a mosaic or a continuous layer of barium dioxide or titanate can serve for this purpose.

It is obvious that image tubes **1**, **24**, **32** or **35** described above, may also be adapted for direct reproducing of invisible images in a visible form, without transmitting them to receivers. In such case, the electron beam irradiating the photocathode **6** or **36**, after being modulated by the potential pattern produced by invisible radiation in said photocathode, is focused on a fluorescent screen disposed in the same tube. The impingement of said modulated electron beam on a fluorescent screen will produce a fluorescent image having the pattern of the original invisible radiation image.

In modification of my invention shown in Fig. 5, the invisible radiation image **3** is projected onto the pick-up tube **60**. The invisible radiation sensitive tube **60** has photocathode **36**, which has the same construction as photocathode used in the tube **35**, illustrated in Fig. 4. The X-ray or neutron image produces in the dielectric layer **38** a current of electrons and "positive holes," as was explained above, which has the pattern of said X-ray image. The charges migrate to the side of the layer **38** facing the electron gun **59** and produce a potential pattern on its surface. The photocathode **36** is irradiated by electron beam **61** from the electron gun **59**. The electron beam **61** is modulated by the conductivity and potential pattern **11** on the photocathode **36**. The returning electron beam **61a** carries, therefore, image corresponding to said pattern. The returning electron beam **61a**, after intensification by acceleration and by electron-optical diminution, is projected on the storage target **22a**, as was explained above. The sensitivity of image tube **60** can be increased by irradiating photocathode **36** with electron beam **14** in two steps, as was explained above. In the first period, the build-up of conductivity and potential image is accomplished. In the second period, said image is read by said electron beam **61** and is stored in target **22a**. The storage target is scanned by electron beam **64** from the electron gun **65**. The scanning electron beam **64** is given helical motion, which means an additional transverse velocity. This is accomplished by the use of two electrodes **67** and **68** disposed on both sides of the scanning beam **64**. The electrodes **67** and **68** are provided with a positive potential from an extraneous source of electrical energy. The helical motion may also be produced in other ways, such as, for example, by misalignment of the electron gun **65** in relation to the axial focusing field. The scanning electron beam is decelerated in front of the storage target **22a** by means of ring electrode or preferably by using a mesh screen. The scanning electron beam **64** neutralizes the positive charges in target **22a** and is, therefore, modulated by said pattern of the electrical charges. The returning electron beam consists of two different groups of electrons. One of them **64b**, is made of electrons reflected by the target **22a**, whereas the other group **64a**, is formed by scattered electrons. The reflected electrons correspond to dark areas of the picture. The scattered electrons correpond to the light areas of the picture, because the light areas produce stronger charges on the target, as was explained above. The returning electron beam, consisting of these two different groups of electrons, is deflected from the original path of the scanning beam **64** by electrodes **69** and **70**. These electrodes may be planar or curved and do not have to be described in detail, as they are well known in the art.

In front of the electron gun **65**, there is disposed cylindrical electrode **71**, which pulls the secondary electrons from the first multiplying dynode **49a** into the multiplier **49**. A disc **71a** is connected with the electrode **71** or forms a part of it. The disc **71a** has an opening **71b**, which may be of a circular or rectangular shape. The electrodes **69** and **70** cause displacement of the returning electron beam downwards. As was explained above, the scattered electrons **64a**, having larger transverse velocity than the reflected electrons, are outside of the beam of the reflected electrons **64b**. Therefore, by depressing the returning electron beam by electrodes **69** and **70**, the reflected electrons may be directed against the disc **71a** below its aperture **71b** and will be eliminated, whereas the scattered electrons will be admitted into aperture **71b**. In this way, both groups of electrons may be separated from each other. The scattered electrons, after passing through the aperture **71b**, strike the first dynode **49a** of the multiplier **49**. The secondary electrons are drawn by the action of the electrode **71** to the next stage of the multiplier, which is around and in the back of the first stage. This process is repeated in a few stages, resulting in a marked multiplication of the original electron signals. The signal currents from the last stage of the multiplier are converted over a suitable resistor into video signals. The strongest video signals will correspond to the highlights of the picture, because the strongest scattering of electrons takes place at the most positively charged areas of the storage target **22a**. In front of the storage target **22a** in some cases, there may be disposed a mesh screen, which provides a uniform electrical field for improving resolution of the picture. Video signals are fed into television amplifiers **72** and then are sent by coaxial cable **73** or by high frequency waves to the receivers of kinescope type **74** or facsimile, in which they are reconverted into visible images **75** for inspection or recording.

The pick-up tube **60** may operate as a storage tube by exploiting the photoconductive lag of the photocathode **36**, as was described above.

A great improvement in the operation of the X-ray or neutron image intensifying system may be obtained by the use of a special storage tube for video signals. By the use of storage tube, the scanning time in the X-ray pick-up tube can be prolonged, as well as the frame time, resulting in a proportionally greater electron output of the composite photocathode and better signal to noise ratio. Also, the flicker caused by prolongation of frame time can be in this way successfully eliminated.

Another advantage of the use of the storage tube in the X-ray intensifying system is the reduction of total X-ray exposure, which is given to the patient, because X-ray radiation does not have to be maintained any more while studying the X-ray image. This saving of the X-ray exposure will make it possible to use strong but short bursts of X-rays or neutrons without endangering the patient. The possibility of using a strong X-ray or neutron beam will markedly improve signal to noise ratio of the whole system and will, therefore, make it possible to obtain pictures of good detail and contrast even of the thickest part of the body.

The X-ray image in the form of the video signals is sent from any of the X-ray pick-up tubes described above to the storage tube **77** and is deposited there in the form of electric charges, by means of modulating the scanning electron beam **78** of said storage tube, in a special target **79**, in which it can be stored for a predetermined time.

The storage target **79** consists of a thin perforated sheet of metal or other conducting material, or of a woven conducting wire mesh **79a**. On the side of the target opposite to the electron gun, there is deposited by evaporation storage material **79b** in such a manner that openings **80** in the target should not be occluded. In some cases, on the side of the target facing the electron gun, there is deposited by evaporation, a thin metal coating to prevent leakage of charges. The scanning electron beam **78** is produced in the storage tube **77** by the electron gun **81** and is modulated by incoming video signals from the X-ray pick-up tube **60**. The scanning electron beam is focused and deflected to produce television-like raster by electromagnetic or electrostatic means, which are well known in the art. This scanning electron beam should have the finest spot compatible with the required intensity of beam. Between the electron gun and storage target **79**, in close spacing to the target, there is mounted a fine mesh conducting screen **83**. On the opposite side of the storage target, there is disposed a metal electrode **84**, which acts as an electron mirror during the writing phase of operation and as a collector of the electrons during the reading phase.

The scanning beam is decelerated between the screen **83** and the target **79**. Then it passes through the openings **80** in the target **79**. The reflector electrode **84** during writing is kept at the potential negative in relation to the cathode of the electron gun **81**. Therefore, the electrons of the scanning beam are repelled by it, fall back on the storage target **79** and deposit thereon varying charges at successive points according to the amplitude of modulating input signals from the X-ray pick-up tube **60**. The best way of operating my system is to have the storage surface at zero potential or at cathode potential and then to write on it "positive," which means to deposit positive charges. This can be accomplished by adjusting the potential of the surface of the storage target so that its secondary emission is greater than unity. The secondary electrons will be collected by the conducting mesh **79a** of the storage target and positive charges will be left on the storage surface. These positive charges deposited on the storing surface of the target may be stored thereon for many hours depending on the type of the storage material **79b** which was used. Whereas $BaF_2$ has a time constant of 0.1 second, $CaF_2$ has the time constant of 50 hours.

When the stored image is to be read, the potential of the electron reflector **84** is made more positive than the potential of the storage screen mesh **79a**, so that it will act now as a collector of electrons. Therefore, the scanning electron beam **78** after passing through the perforations **80** in the target **79** will land on the collector **84**. The passage of the scanning electron beam is modulated by the pattern of deposited charges on the storage target. The greater the positive charge, the more electrons will pass through the openings **80** in the target. The less positive the stored charge, the fewer electrons will be transmitted through these openings. In this way, the electron beam **78** scanning the storage target in the usual television-like raster will be modulated by the stored image. The transmitted electrons will be collected by the collector **84** and will be converted over suitable resistor into video signals **85**. The transmitted electrons may also be multiplied by using as a collector **84** an apertured electrode and deflecting fields to make said electrons pass through aperture **84a** in said electrode in succession and to be fed into multiplier **86** before converting them into video signals. This multiplication system is well known in the art, as evidenced by image dissector of Farnsworth and, therefore, does not have to be described in detail. Video signals, having the pattern of the original X-ray or neutron image, are amplified and transmitted by coaxial cable **73** or by high frequency waves to receivers. Receivers of various types, such as kinesopes **74**, skiatrons, facsimile receivers, electro-graphic cameras, may be used to reproduce images for inspection or recording. Also the non-transmitted, returning electrons **78*a*** may be used for producing video signals.

After the stored image has been read and no further storage is desired, it may be erased by the use of the scanning electron beam **78** and by adjusting the potential of the storage target to the value at which the secondary electron emission of its storing surface is below unity. In such a case, the target will charge negatively to the potential of the electron gun cathode. The potential of the reflector in the erasing phase of operation must be more negative than of the storage target, so that the scanning electron beam will be repelled to the storage target and will neutralize the stored positive charges.

It is obvious that the tubes **1**, **24**, **35** or **69** may also serve for receiving and reproducing invisible supersonic images, if the photocathode **6** or **36** respectively is a mosaic of quartz, barium titanate or dioxide, ammonium phosphate, potassium tartrate or other supersonic radiation sensitive material. If the resistivity of supersonic radiation sensitive material is big enough, instead of a mosaic a continuous layer thereof may be used as well.

As various possible embodiments might be made of the above invention and as various changes might be made in the embodiment above set forth, it is to be understood that all matter herein set forth or shown in the accompanying drawings, is to be interpreted as illustrative and not in a limiting sense.

I claim:

1. A vacuum tube comprising in combination a first screen having an imperforate layer of material converting an invisible radiation image into an electrical pattern corresponding to said image, said layer receiving said invisible radiation through the wall of said tube, means for producing a broad electron beam, means for decelerating said electron beam and directing said broad electron beam to said screen for modulating said electron beam with said electrical pattern and for reflecting said electron beam from said screen by said electrical pattern, and a second screen for receiving said reflected electron beam.

2. A vacuum tube comprising in combination a first screen having an imperforate layer of material converting an invisible radiation image into an electrical pattern corresponding to said image, said layer receiving said invisible radiation through the wall of said tube, means for producing a broad electron beam, means for decelerating said electron beam and directing said broad electron beam to said screen for modulating said electron beam with said electrical pattern and for reflecting said electron beam from said screen by said electrical pattern, a second screen for receiving said reflected electron beam, and means for converting said reflected electron beam into electrical signals.

3. A device as defined in claim 1, which comprises in addition means for producing a scanning electron beam.

4. A device as defined in claim 2, in which said first screen comprises a plurality of different photoconductive materials.

5. A device as defined in claim 2, in which said first screen comprises a layer of piezo-electric material.

6. A device as defined in claim 2, in which said layer converting an invisible radiation image into an electrical pattern has an exposed surface and which device comprises in addition means for irradiating said layer with a visible light.

7. A device as defined in claim 2 in which said first screen comprises in addition fluorescent means and in which device said layer producing electrical pattern is responsive to the fluorescent light.

8. A vacuum tube comprising in combination a first screen having an imperforate layer of material converting an invisible radiation image into an electrical pattern corresponding to said image, said layer comprising piezo-electric material and receiving said invisible radiation through the wall of said tube, means for producing a broad electron beam, means for decelerating said electron beam and directing said broad electron beam to said screen for modulating said electron beam with said electrical pattern and for reflecting said electron beam from said screen by said electrical pattern, and a second screen for receiving said reflected electron beam.

9. A device as defined in claim 8, in which said second screen comprises fluorescent means.

10. A device as defined in claim 8 in which said piezo-electric layer is of mosaic type and has an exposed surface.

11. A device as defined in claim 1 in which said first screen comprises a plurality of different from each other photoconductive layers disposed one after another.

12. A device as defined in claim 11 in which said first screen comprises fluorescent means.

13. A device as defined in claim 11, which comprises in addition a mesh screen closely spaced to the exposed surface of said first screen.

14. A device as defined in claim 1 in which said layer receiving said invisible radiation is of mosaic type and in which said second screen comprises fluorescent means.

15. A device as defined in claim 2, in which said layer receiving said invisible radiation is of mosaic type.

**References Cited** in the file of this patent

UNITED STATES PATENTS


| | | |
|---|---|---|
| 2,520,240 | Flory | Aug. 29, 1950 |
| 2,527,632 | Graham | Oct. 13, 1950 |
| 2,533,073 | Weimer | Dec. 5, 1950 |
| 2,544,753 | Graham | Mar. 13, 1951 |
| 2,555,424 | Sheldon | June 5, 1951 |
| 2,622,219 | Schagen | Dec. 16, 1952 |