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[54] IMAGE-RECORDING METHOD AND DEVICE

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[51] Int. Cl. **G02b 27/22**

[58] Field of Search .... 350/3.5; 161/160; 346/76 R; 250/65.1; 117/8, 11, 37

[56] **References Cited**

OTHER PUBLICATIONS

Heflinger et al., " Holographic Interferometry," 37 Journal of Applied Physics 642 (2/1966).

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Assistant Examiner—Robert L. Sherman
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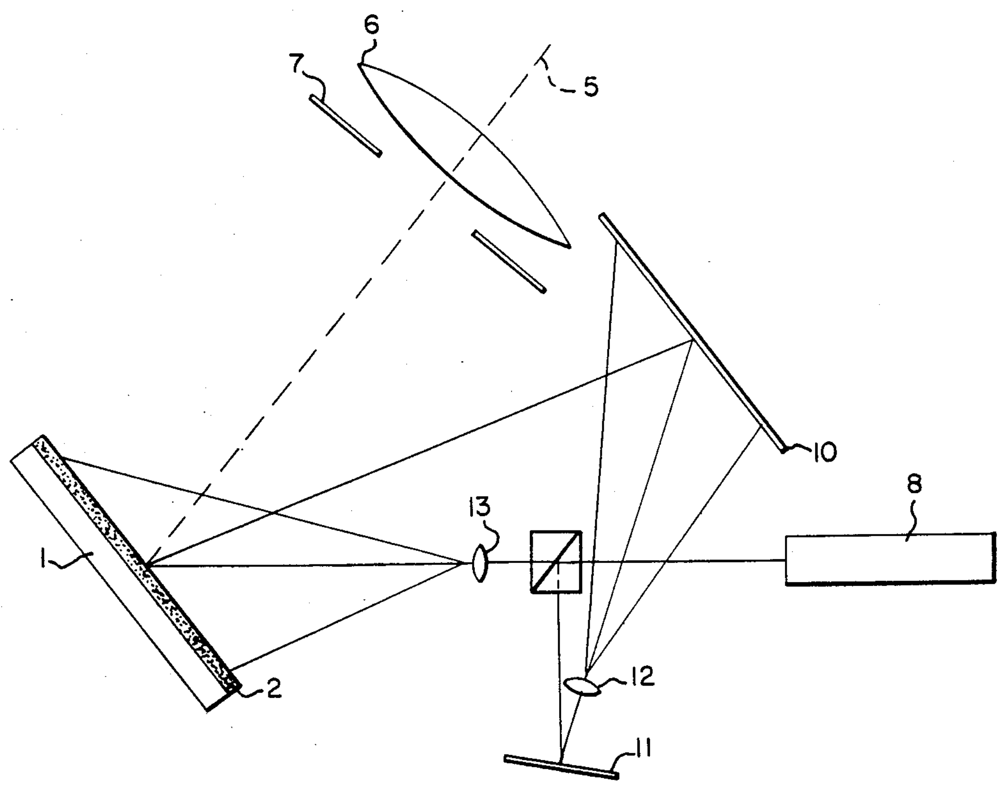
[57] **ABSTRACT**

Reproducible images of the transverse distribution of energy in a beam of radiation are formed by focusing the beam on a layer of an energy-absorbing substance of low heat conductivity which topically expands in proportion to the equivalent heat content of the radiant energy pattern in the beam to form a steric image thereof and recording the steric image thus formed by double-exposure holography. The energy-absorbing reactive layer may be formed of natural substances, such as cork, or of artificial compositions, such as urethane or styrene foams. The reactive layer may be supported on a plate of metallic, plastic or vitreous material, and may be coated with an energy-absorbing coating.

4 Claims, 3 Drawing Figures



PATENTED FEB 22 1972 3,644,014

FIG. 1.

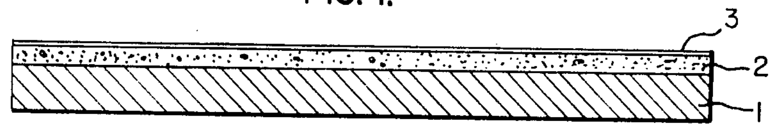


FIG. 2.

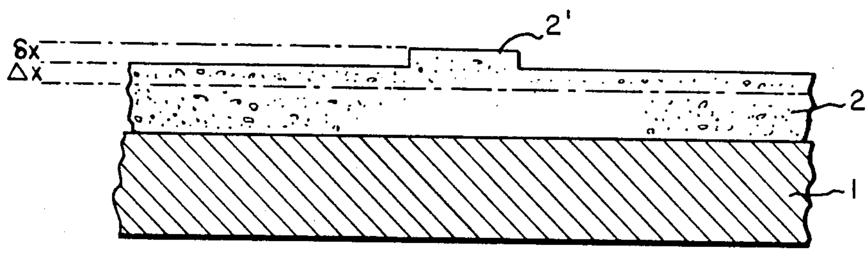


FIG. 3.

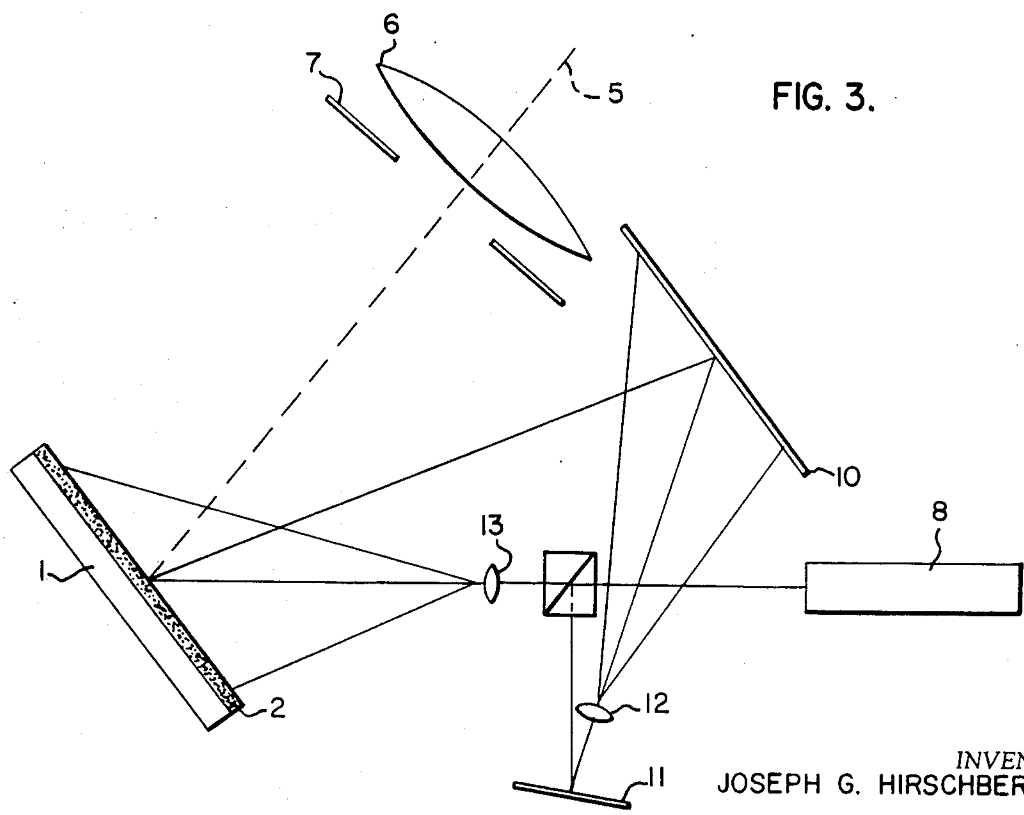


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IMAGE-RECORDING METHOD AND DEVICE

The invention relates to a method and apparatus for forming reproducible images of the energy pattern in beams of radiation.

Of the total energy spectrum which might be used for the production of reproducible images only a small portion has so far been utilized with simple apparatus. The bulk of the infrared, together with the entire supersonic spectrum, lies in this category. For these regions of the energy spectrum one must generally employ complex and expensive apparatus, such as the Evaporograph (G. W. McDaniel and D. Z. Robinson, Appl. Optics 1, 311 (1962)) or scanning devices (R. Bowling Barnes, Appl. Optics 7, 1673 (1968)).

The object of the present invention is the provision of a simple method and apparatus for producing reproducible images of energy patterns adaptable to a wide range of energy forms such as infrared, microwave and supersonic radiation. This object is attained by focusing a beam of transversely patterned radiant energy upon a layer of energy-absorbing substance of low heat conductivity which topically expands in proportion to the equivalent heat content of the radiant energy pattern in the beam to form a steric image thereof and recording the steric image thus formed by steric image holography.

The energy absorbing reactive layer may consist of a natural or artificial microcellular substance such as cork or urethane or styrene foam and may advantageously be supported on a metallic, plastic or vitreous plate. The reactive layer may be coated with an energy-absorbing composition.

The principles of the invention will be further described with reference to the accompanying drawing in which:

FIG. 1 is a transverse section of a typical steric image forming assembly embodying the principles of the invention;

FIG. 2 is a diagrammatic greatly enlarged section showing the formation of the steric image on the reactive layer of the assembly of FIG. 1; and

FIG. 3 is a diagrammatic representation of apparatus for forming reproducible images by the method of the invention.

In FIGS. 1 and 2, 1 is a support plate of metal, plastic, glass or the like and 2 is a layer of energy-absorbing material such as cork or plastic foam, which may have an energy-absorbing coating 3, for example, paint.

The formation of a steric image in layer 2 by differential expansion therein is effected as follows. Assume an image focused on layer 2, all of the image of which is absorbed within a slab of thickness Δx of the layer. In this slab there will be a resulting temperature distribution in the vertical direction, neglecting lateral heat flow, of $T(x,t)-T_o$, where T_o is the original temperature of the slab and t is the time of exposure. The change in thickness δx of the slab is given by

$$\delta x=\gamma\int_{x=0}^{\Delta x}[T(x,t)-T_o]dx \qquad (1)$$

where γ is the scalar coefficient of expansion.

To determine $T(x,t)-T_o$, we must consider the various sources of energy received by the active layer. If the rate of temperature rise of the slab is the energy equation may be written

$$A\int_{x=0}^{\Delta x}\frac{\partial T}{\partial t}c_p\rho dx=A\int_0^{\infty}\alpha(\lambda)H_\lambda d\lambda-A\sum_i q_i \qquad (2)$$

where A is the area of the image, c_p is the specific heat of the material in the slab, ρ is the density of the slab material, H_λ is the spectral irradiance falling on the slab, $\alpha(\lambda)$ is its spectral absorbance, and $\Sigma q_i A$ is the sum of all losses of heat from the slab. These would include conduction, convection and radiation losses.

The exact solution of Equation (2) is not necessary, since to obtain the expansion δx we will integrate over the whole slab thickness Δx. Thus we can use the temperature T averaged over x in the slab. The average increase in temperature $T-T_o$ is given by

$$T-T_o=\frac{\tau}{c_p\rho\Delta x}\int_0^{\infty}\alpha(\lambda)H_\lambda d\lambda-\sum_i q_i\tau \qquad (3)$$

where τ is the exposure time. The expansion,

$$\delta x=\frac{\gamma\tau}{c_p\rho}\int_0^{\infty}\alpha(\lambda)H_\lambda\delta_\lambda-\sum_i q_i\tau. \qquad (4)$$

or δx is independent of the depth of the heated layer Δx.

It will be seen from Equation (4) that to maximize δx for a given exposure time τ we should utilize a material of small c_p and ρ and large γ, while keeping the absorptivity α high. The losses q_i should also be kept as low as possible.

The bas-relief or steric image formed on layer 2 in this way is converted into a reproducible image by double-exposure holography or interference photography (L. O. Heflinger, R. F. Wuerker and R. E. Brooks, Jour. Appl. Phys. 37, 642 (1966)) as illustrated in FIG. 3.

In the apparatus of FIG. 3, the radiant energy beam 5 can be focused by lens 6, or an equivalent mirror, through shutter 7 on reactive layer 2.

The beam from laser 8 can be focused by means of beam splitter 9 on photographic film 10, both directly by way of mirror 11 and lens 12 and by reflection from layer 2 by way of lens 13.

In operation, (a) radiation shutter 7 is closed. (b) An exposure with the laser is made, forming a hologram on the photographic film 10. (c) The radiation shutter is opened, and the radiation lens 6 or mirror or other focusing device forms the radiation image to be recorded on the active layer 2. The active layer is allowed to expand to the proper degree. The time τ required will depend on many factors such as the nature and intensity of the radiation, the contrast in the object and the final image desired, the properties of the active layer, and the ambient temperature. (d) A second exposure with the laser is made, forming a second hologram in the film. (e) The film is developed, and with the laser in the same orientation to the film as the reference beam R, the holograms are photographed. There will be interference between the images in the two holograms resulting from the differences δx, in the level of the receiving plate surface. In other words, the differences, δx, in FIG. 2 will be recorded as light or dark areas in the hologram interferogram.

The principle of the double-exposure hologram is to obtain two-beam interference between the wave-front coming from the undisturbed surface of the active layer and that from the surface after being acted upon by the radiation to be imaged.

The amplitude of the undisturbed wave-front can be expressed:

$$A_u=\frac{s}{r}\left(A_o e^{i(\omega t-kr)-2ikx(y,z)}\right) \qquad (5)$$

wherein A_o is the maximum incident amplitude, ω the frequency, k the wavenumber and r the distance from the surface to the photographic plate; s is the reflectivity where $x(y,z)$ expresses the departure of the surface from planarity. The factor 2 comes from the fact that the light is reflected.

After being affected by the radiation exposure, the surface will be expanded by $\delta x(y,z)$ as explained above. The resulting amplitude will be

$$A_s=\frac{s}{r}\left(A_o e^{i(\omega t-kr)-2ikx(y,z)-2ik\delta x(y,z)}\right) \qquad (6)$$

A_u and A_s differ only in the factor $\frac{s}{r}A_o e^{-2ik\delta x(y,z)}$.

This means that the resulting interferogram is given by

$$M=I_o\cos^2[k\delta x(y,z)] \qquad (7)$$

where I_o is the maximum intensity.

Maxima of M occur where $k\delta x(y,z)=m\pi$ or, since $k=2\pi/\lambda$, there will be an interference fringe for each change in δx of $\lambda/2$.

Since at $(2m-1/2)\pi$, $M=0$, the fringes are very clear and a small fraction of a fringe, usually less than 1/10, is easily detectable. This means that a shift δx of $\lambda/20$ can be measured. Using the light of a convenient He-Ne laser, this amounts to $3.16\times10^{n/n}$ cm.

From the results of the previous sections, an estimate of the sensitivity can be obtained. As we have concluded, the change in surface level δx should be $\lambda/20$ for easy detection, a value we shall use for calculation. Equation (4) gives δx in terms of the properties of the active layer, the exposure time, the irradiance, and the various losses. These include radiation losses, conduction losses in the y and z directions, conduction losses to the atmosphere, and convection losses. It can be shown that these losses are all small compared to the energy required to heat the active layer, represented by the first term on the right side of Equation (4) which we will accordingly write

$$\int_0^\infty \alpha(\lambda)H(\lambda)d\lambda = \frac{c_p\rho\delta x}{\gamma\tau} \tag{8}$$

If we made the reasonable assumption that $\alpha(\lambda)$ is constant over the energy range used and equal to 0.8, we can evaluate the left side of 8 in terms of the increment of integrated irradiance dH, obtaining

$$dH = \frac{c_p\rho\delta x}{0.8\gamma\tau} \text{ cal. cm.}^{-2} \text{ sec.}^{-1}. \tag{9}$$

Using cork for the active layer material, c_p=0.48 cal./gm., ρ=0.13 g./cc. $\gamma=1\times10^{-4}$ cm./degree C.

Taking δx as 3.16×10^{-6} cm. as indicated above, and τ=10 seconds, the minimum detectable irradiance dH is 2.5×10^{-4} cal. cm.$^{-2}$ sec.$^{-1}$.

We will make an estimate of sensitivity using infrared radiation. The Stefan-Boltzman Law states:

$$\int_0^\infty W(\lambda)d\gamma = \sigma T$$

where T is the source temperature and σ is 1.35×10^{-12} cal. cm.$^{-2}$ K.$^{-4}$ sec.$^{-1}$, and an emissivity of unity is assumed. Differentiating:

$$dT = \frac{dW}{5.4\times10^{-12}T^3} \tag{10}$$

For an object temperature T of 500° K.

$$dT = 1.5\times10^3 dW$$

The relationship of dW, the increment of radiance emitted by the object to dH, that of the irradiance received by the active layer is given by:

$$dH = dW\Omega M^2/\pi$$

where Ω is the solid angle over which emitted energy is collected by the optical system and M is the magnification. Substituting for dW

$$dT = \frac{0.15\times10^4\pi dH}{M^2\Omega} \tag{11}$$

If we now assume M=1, Ω=0.5 steradians, and $dH=2.5\times10^{-4}$ cal.cm.$^{-2}$ sec.$^{-1}$ for detectability as calculated above, dt, the minimum detectable temperature increase of this source is 2.3° C.

The sensitivity can be increased by any of a number of methods including the utilization of a more sensitive reaction layer than cork, the use of shorter wavelength radiation (ultraviolet) for making the hologram, cooling the reactive layer, and making use of higher orders in the holograms.

I claim:

1. A method of forming reproducible images of the transverse distribution of energy in a beam of radiation which comprises focusing the beam on a layer of an energy absorbing substance of low heat conductivity which expands topically in proportion to the equivalent heat content of the radiant energy in the beam to from a steric image thereof and recording, the steric image thereof by double exposure holography, said recording comprising first recording a hologram of the undisturbed surface of the layer and then recording a hologram of the surface after being acted upon by the radiation.

2. A method as defined in claim 1 wherein the energy-absorbing layer comprises a microcellular organic material.

3. A method as defined in claim 2 wherein the microcellular organic material is a plastic foam.

4. A method as defined in claim 2 wherein the microcellular organic material is cork.

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