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HIGH-RESOLUTION OPTICAL IMAGING ON THERMOPLASTIC FILM

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HIGH RESOLUTION OPTICAL IMAGING ON THERMOPLASTIC FILM

ABSTRACT

Experimental details of a novel method for recording optical images is presented. In this method, a photoconductive layer arranges electric charges according to the optical image projected onto it. The differential electric fields thus produced, squeeze a thermoplastic layer into ridges which constitute the final image. The interference of two laser beams ($0.63\text{ }\mu\text{m}$) which formed an optical image of 1000 cycles/mm was clearly and accurately recorded. The spatial frequency response differs from the conventional photographic method and is well suited for holograms. The image can be erased and the medium reused many times. The thermoplastic layer alone can be "written on" by charges applied by touching with a thin wire. A program with the aim of optimizing the medium and processing is suggested.

INTRODUCTION

We recorded optical images on a thermoplastic-photoconductor film combination. This combination has the advantages of high resolution, good sensitivity to light, and dry, fast, in place development. The film is erasable and reuseable. This method of recording images may possibly be used at $1.06\text{ }\mu\text{m}$ (light from a neodymium laser) where photographic film is limited in resolution. Although we have not yet determined the sensitivity at $1.06\text{ }\mu\text{m}$, the film does display light absorption at this wavelength.

In this process the image is formed by surface distortions of a thin thermoplastic layer. These distortions correspond to the optical image which has fallen on an underlying photoconductive layer. These two layers are backed with a glass plate having a grounded layer (see Fig. 1). The medium is placed near one or more ionizer wires charged to 3.9 kV. Air around the wire is ionized by the corona discharge and ions are attracted

Fig. 1. The recording medium.

to the thermoplastic surface. When a light image falls on the underlying photoconductive layer, regions of different resistivity are formed. Electrons move from the conductive layer to the underside of the thermoplastic layer in a pattern determined by the light image. The ionizer wires are then recharged to equalize the surface potential. At this time there is a higher electric field in those areas of the plastic where light has fallen. When heated the viscosity becomes low near the melting point; the plastic is squeezed from regions of high electric field to those of low electric field. This rearrangement of the surface constitutes the image. It may be observed by the refraction and diffraction of light.

This type of process has been studied in a number of industrial laboratories. One of the latest descriptions of the method is by Credelle and Spong¹. We used their recipe to guide our work, although there were many details to rediscover. This report points out the advantages of imaging on thermoplastic and describes some of the details and problems not discussed in Ref. 1. We believe that this process can be used in a practical recording tool.

EXPERIMENTAL

Recording Medium

The backing material for the recording medium is glass coated on one side with a transparent conductive surface. For the medium to be self-heating the surface resistivity of the conducting layer should be 20-100 $\Omega/\text{sq.}$ For our units this required a heating voltage of 50-115 V. We used Nesatron* glass from Pittsburgh Glass Co. which has a transparent conductive surface of a thin indium oxide layer, doped with tin oxide. The sample we ordered varied considerably in average surface resistivity. In

* Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

ambient light, a grid work of interference colors, with a spacing of 13 mm, indicated a thickness variation that probably caused uneven heating of the film.

The photoconductive layer (PC) was polyvinyl carbazole (PVK) sensitized with 2,4,7-trinitro,9,fluorenone (TNF). It was applied as a solution in 1,4-dioxane and dichloromethane. The molar ratio of PVK/TNF was 8 and the total concentration was 8% solids. By pulling a Nesatron slide out of this solution at 1.7 mm/s, a film thickness of 2.7 μm was obtained. As the solution evaporated in damp air the surface became milky and TNF crystallites formed. To slow down the rate of evaporation and hence cooling, the slides can be put in a dessicator or enclosed with solvent vapor. This cures the milkiness problem, but some TNF crystallization still occurs. As the slide is withdrawn from the solution, thickness striations parallel to the liquid level form. These can be seen as many interference fringes after the film dries.

Absorption spectra show that TNF, added to the PVK, increases the light absorption by a factor of 10 at a wavelength of 0.5 μm . The contribution of the TNF decreases to zero as 0.8 μm is approached. Beyond this wavelength the PVK by itself has a measurable absorption up to 1.15 μm . Whether this absorption is also accompanied by photoconduction is not yet known. Lardon *et. al.*² found that PVK-TNF had appreciable photoconductivity at 0.65 μm . Our PVK, which may contain impurities, absorbed higher wavelength light than theirs did.

The thermoplastic layer (TP) was coated over the photoconductive layer. It was about 0.5 μm thick and formed by pulling the slide, at 1.7 mm/s, from a 20% solution of Staybelite Ester 10 (the glycerol ester of a hydrogenated wood rosin made by Hercules, Inc.).

Recording Process

The medium, on a Nesatron slide, (25 mm $\times$ 76 mm) was held to a base plate by a spring clip at each end. The clips made contact with 3-mm wide silver-paint electrodes. These distributed the current to the Nesatron

conducting layer. Two 80- μm -diam, tungsten ionizer wires were parallel and spaced 15 mm apart. A fine-meshed copper screen was placed 5 mm above the wires at ground potential. The upper surface of the medium was 7.3 mm below the ionizer wires and grounded. The wire voltage was such that the corona current charged the surface to about 300 V in 5 s.

He-Ne laser light (0.633 μm) was one of the sources used to form an image and was on concurrently with the ionizer. This light had a power density of 5 W/m^2 (0.5 mW/cm^2) and being on 5 s gave a total light energy of 25 J/m^2 (2.5 mJ/cm^2). By splitting the beam and reconverging it at an angle of 40° , a 1000 cycle^{*}/mm diffraction-interference pattern was produced.

Voltage, which was calculated to dissipate 50 W, was used in the actual imaging of the thermoplastic layer. Thus, for a typical heating time of 2.5 s, the energy surface density applied to the film was 70 kJ/m^2 . Based on the specific heat of the glass, it was expected that temperature of the slide would rise to 52°C . Since the Staybelite Ester 10 has a softening point of 83°C , the coatings on the slide must reach a temperature above the final equilibrium temperature.

RESULTS

In the first experiments the thermoplastic layer was studied by itself on a glass microscope slide placed on a grounded metal plate. The layer of Staybelite Ester 10 was "written on" with a 80 μm -diameter, tungsten wire having 2 kV applied to it. The plastic layer itself was thus subjected to an electric field of about 2 MV/m. The result is shown in Fig. 2. In these early experiments the slides were placed in an oven after exposure. The resulting transfer and heat-up time may have been sufficient for the initial charge along the central track to leak into the "lobes" visible in the figure.

* A cycle is equivalent to a line with a dark strip and a light strip.

Fig. 2. Thermoplastic layer after having been "written" on with a 2-kV-potential wire (40X).

By adjusting the amount of charge that fell on the surface and the subsequent temperature-time "development" schedule, a "frost" pattern was produced. When the surface, with a uniform charge on it, was heated to the softening point of the rosin (83°C), a wrinkling or frost formed on the surface as shown in Fig. 3. Although in general the pattern is random, there is an obvious 4- μ m spacing of the lines. Cressman³, working with polystyrene (Piccolastic A-75), found that there is a threshold for the surface potential (or surface charge density) below which frost doesn't form. He postulated that the surface tension, which tends to keep the surface flat, is weakened by the electric field. Budd's⁴ "Dynamical Theory of Thermoplastic Deformation" used an effective surface tension coefficient which was a function of the uncharged surface tension coefficient, the surface charge density, and the energy of the deformed surface. This coefficient was then used to calculate the growth rate for a given deformation wavelength. Figure 4 is a photograph (14X) of a frost patch and shows the shadow cast by a chip of cover slide glass (the chip moved after the image formed.)

The entire sequence of the recording process was next tried with a small tungsten lamp which projected a silhouette of the copper screen onto the photoconductive layer. The results are shown in Figs. 5, 6, and 7. Figure 5 shows an overall view, Fig. 6 shows the screen and a faint reproduction of the image, and Fig. 7 is a better picture of the image.

When the TP was heated above the temperature required for development, the image was erased. Under these conditions the increased dark current lets the surface charge leak off and the surface tension smooths the surface. Thus the image is erased and the medium can be reused many times. By using a TV camera near the screen many experiments were run to optimize the amount of charge, the amount of light, and the development conditions. As can be seen from the figures, the frost does not extend uniformly over the whole surface. The limited region of uniform charge deposition, the uneven thickness of the layers, and the suspected uneven heating all contribute to this.

Fig. 3. Photomicrograph (500X)
of the frost image; taken
using reflected light,
differential interference
contrast microscopy.

Fig. 4. Photographic (14X) of a
frost patch and the shadow
cast by a glass chip.

Fig. 5. Overall view (3.5X) of the image of the copper screen.

Fig. 6. Photograph (13X) of both the screen and the image.

Fig. 7. The screen image (13X).

In another experiment we used two beams from a He-Ne laser. The beams intersected at 40 deg, forming an interference pattern with a fringe spacing of 1000 cycles/mm. The light intensity ($0.633 \mu\text{m}$) at the image place was 5 W/m^2 (0.5 mW/sq cm). The ionizer and the light source were on together 5 s, then the heater was on for 3 s. A photomicrograph of the resulting image (Fig. 8) was taken using Zeiss differential interference contrast microscopy with reflected light. The image on the slide is clearly visible. It is 3 mm in diameter with diffraction colors visible by reflection. When a He-Ne laser beam strikes the image, bright clear first-order diffraction spots appear in transmission and reflection. For comparison, the same interference pattern was recorded on Agfa Scientia 10E75 photographic plates (Fig. 9).

DISCUSSION

These recorded images differ from photographic images, where light of varying intensity is recorded as varying optical density on the film. In the present method, the difference in light intensity causes a distortion in the surface of the thermoplastic layer. In this sense it is related to differential interference contrast microscopy where the image results from differences between two closely spaced points of the object. It accentuates the small details of an object. This follows naturally when it is considered that the distortion of the $0.5 \mu\text{m}$ thermoplastic layer results when plastic flows from one point to another.

This difference can be made more quantitative by considering the spatial frequency response curve. Figure 10 compares, in a rough way, thermoplastic imaging with several types of photographic imaging types. The modulation factor is the actual response (image amplitude) divided by the ideal response (ideal image amplitude).⁵ The curve for the Agfa plates was estimated assuming from Fig. 9 that the resolution is low at 1000 cycles/mm. The thermoplastic curve was sketched in for a dominant frequency of 1000 cycles/mm with a bandwidth of 500 cycles/mm, as mentioned by Credelle and Spong¹. Actually the spacing on Fig. 3 indicates this curve should extend down to 250 cycles/mm. Here again one must remember that the response is a surface distortion in one case and optical density in the other two. The interference pattern from the laser beams was used because

Fig. 8. Interference pattern image (~1000 cycles/mm) recorded on thermoplastic (1000X, reflected light, differential interference contrast).

Fig. 9. Interference pattern image (~1000 cycles/mm) recorded on Agfa Scientia 10E75 (1000X, reflected light, differential contrast).

Fig. 10. Spatial frequency response curve.

the resulting frequency was within the bandwidth of the thermoplastic layer and was uniform over a wide area. By modulating one of the beams with an object, the image would have become a hologram. Because of the high resolution capability of this image forming method, it is ideally suited for making holograms. Of the many types of phenomena that could lead to holograms, plasma diagnostics is certainly one that could be of value to the Laboratory. A laser beam traversing a plasma would be partially absorbed and also deflected by refractive index gradients. The present method gives an image within seconds after the event, and by erasing, many sequential events can be studied over a period of minutes. The general advantages of holograms such as multiple records on one hologram, 3-dimensional pictures, magnification using two different frequencies (i.e., x-rays and visible light) can be exploited.

The high resolution capability can also be used for recording information at high density and hence could be used as a computer memory. For instance, it might be used in the way film is now used in the IBM photo-store. The unusual spatial frequency response can be utilized as a built-in optical filter. As Fig. 8 so vividly illustrates, diffraction gratings can be made. Special variable spacing gratings could be made. These could be used to direct beams of light in precise directions.

We believe that the wavelength limit for photoconduction can be extended to $1.06 \mu\text{m}$. In general, photoconductivity versus wavelength should be studied and the effect of different sensitizers determined. It should be pointed out in this regard that Lardon et al.² believe that the ions from the corona discharge are discharged on contact with the PC. The carriers are then trapped within the polymer. Thermal untrapping accounts for the dark current, and optical untrapping via the charge transfer complex PVK-TNF excitation causes the photoconductivity. In our experiments the thermoplastic layer (TP) was a good insulator. The above explanation could apply if the charge carriers enter from the Nestatron layer. Thus, the extension to photoconductivity at $1.06 \mu\text{m}$ light may involve influencing

trapping levels in the PVK as well as the nature of the PVK-acceptor charge transfer complex.

Also the best method of making a uniform thin coating needs to be found. The viscosity and electrical conduction of the thermoplastic layer should be determined as a function of temperature. A method for heating the film to a precise temperature should be found. Ionizer design should be studied and the optimum time of exposure to light be found. The amplitude of the surface distortion should be studied as a function of light intensity, surface charge density, and heating cycle details. The spatial frequency response should be obtained.

In conclusion, we believe that with some further developmental work a useful imaging system can be attained.

ACKNOWLEDGMENT

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