

Imaging on thermoplastic films: a new recording technique for a real-time coherent light valve

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Received 18 July 1984.

0003-6935/85/040450-04\$02.00/0.

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In competition with digital techniques, coherent optical processors are mainly limited by their real-time input capability.¹ With currently available devices, the physical limits are time-bandwidth or space-bandwidth products of ~ 4000 for 1-D acoustooptic spatial modulators and 500×500 for Pockels effect or other 2-D light valves. The experiments presented here intend to demonstrate the feasibility of achieving values over 4000/line on a raster-scanned 2-D modulator using thermoplastic film. The basic idea is to convert the incoherent sum of holographic fringes and input image into a product by the nonlinear discharge and saturation characteristic of the recording medium. Our experiments had been performed before we learned about recent work at Caltech to utilize a BSO holographic recorder as an input light valve,² which follows a similar approach although the physical mechanism involved and the possible applications are different. The classical properties of thermoplastic recording will be reviewed before describing our double-exposure processing.

Although single-layer devices with photoconductive thermoplastic materials have been used, the standard configuration consists of an organic photoconductive coating on a thermoplastic layer with a glass plate or plastic roll-film substrate. The various recording processes are summarized in most books devoted to optical recording materials³⁻⁶; the exhaustive study by Urbach⁷ is still valuable. The three essential properties of thermoplastic recording are bandpass filtering, random frost noise, and reusable capability limited by fatigue effects and incomplete erasure. The last point is mainly responsible for hindering development of electron-beam addressed thermoplastic light valves⁸ or image converters using fixed plates.⁹ Due to the bandpass effect, a high-frequency spatial carrier is needed, which makes the material well suited for holography¹⁰ but requires screening techniques for incoherent image recording. The frost noise described in the literature is a phase noise. It acts as the grain noise in silver-halide photography and yields an annular spectrum that corresponds to the bandpass characteristic of the thermoplastic film.¹¹ The optimal spatial carrier frequency is of the order of about half of the inverse of the thermoplastic thickness and of approximately twice the recording bandwidth. Typical values range from 1200 mm^{-1} for coated plates to 800 mm^{-1} for industrial roll films and tapes.¹²

Thermoplastic recording basically consists of four steps: electrostatic charging; light exposure; heating (for softening to allow surface deformation); cooling (to freeze the deformation). A variant of this sequential recording is continuous recording, where the first three steps are simultaneously performed together with a reconstruction of the recorded hologram for control before freezing.¹³ In the sequential mode, a recharge step is often added, after the exposure, to increase the modulation efficiency. Since the exposure step

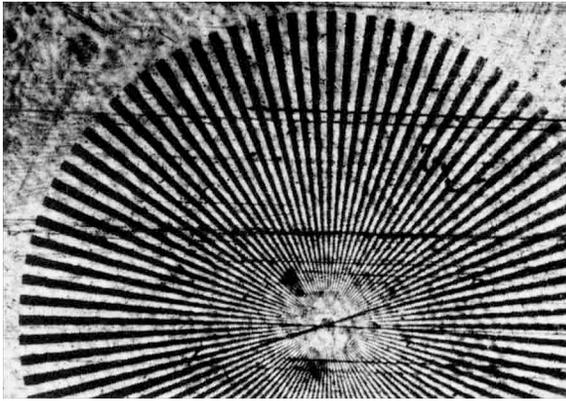


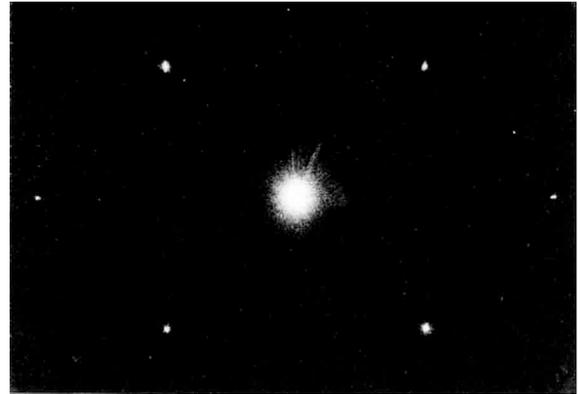
Fig. 1. Laser restitution (+1 order) of a spoke target recorded in the double-exposure mode (image first, carrier afterward).



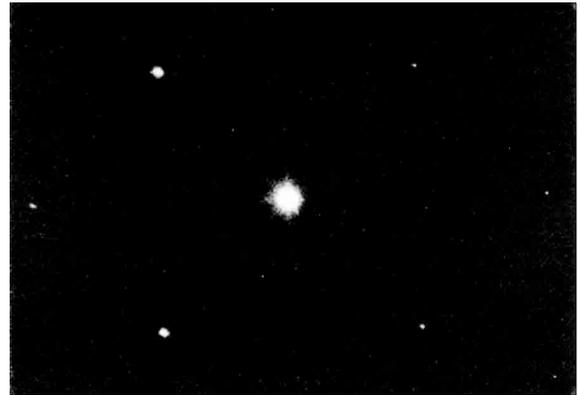
Fig. 2. Quasi-monochromatic restitution (+1 order) of a continuous-tone image (photographic negative) recorded onto the carrier frequency (770 mm^{-1}).

is an electrostatic discharge process, saturation will occur in places where all the charges deposited during the first step have been transferred to the photoconductor-thermoplastic interface. The proposed new mode of operation for light-valve applications, which will now be described, is based on this saturation effect. The applied double-exposure technique consists of first recording interference fringes from two plane waves as a carrier grating and then making a second exposure with the desired image using coherent or incoherent light. (The order of exposures may be reversed.) In that way the spatial carrier modulation of charges on the thermoplastic surface is amplitude modulated or even completely erased according to the object light.

No image will be recorded if the total exposure energy is too low for reaching the saturation effect of the discharge process. This can be overcome if sufficient bias is provided during one of the two exposures or in an additional third exposure with uniform illumination.



(a)



(b)

Fig. 3. Spectrum of a screened positive image (diagonal frequency component 70 mm^{-1}) recorded onto the 770-mm^{-1} carrier: (a) zero order; (b) +1 order.

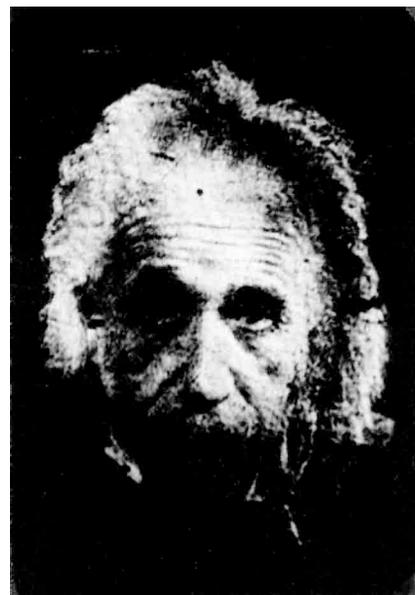


Fig. 4. Fourier transform of Fig. 3(a) after narrowband spatial filtering yielding a reconstruction of the zero-order image (positive) with laser light.

In our experiments a standard holocamera was used, which uses HF-85 roll film manufactured by Kalle-Hoechst AG. This film has a two-layer configuration with thicknesses of $\sim 1 \mu\text{m}$ for both thermoplastic and photoconductive layers. The processing follows the four steps mentioned above. The correctly charged but unexposed film looks milky after development due to the random frost deformation showing a smallest grain size of $\sim 1.1 \mu\text{m}$. When exposing the film with the optimal carrier frequency of $\sim 770 \text{ mm}^{-1}$ the noise solely remains along the dark fringes of the recorded interference pattern.

Three recording modes have been studied using the same input images:

single exposure without a spatial carrier frequency referred to as frost imaging in the literature (*S* mode);

single exposure with a reference beam for image plane holography (*H* mode);

double exposure, namely, successively writing a carrier grating and the image (*D* mode).

Obviously the modulation of the frost *S* and that of a carrier grating *D* seem to be based on the same erasure mechanism. For the image reconstruction three types of light source were used: He-Ne laser *L*, white-light *W*, or quasi-monochromatic light with a spectral width of 8 nm *M*. The results were similar for *W* or *M* (except for the resolution, some blurring being observed with *W*). Thus the comparison between the results from the three recording modes will be restricted here to *L* or *W* reconstruction.

H-mode (L or W): In the zero order, no spectrum can be observed and no image reconstructed; the spectrum for the +1 or -1 diffracted order of the carrier frequency shows low-pass filtering at $\sim 850 \text{ mm}^{-1}$, and the corresponding image is positive and amplitude modulated (visible without phase-contrast filtering according to the bandpass process).

S-mode: On-axis illumination yields a noisy spectrum and image with *L*, while a high-resolution positive image is observed with *W* (showing good contrast when correcting for the bias level with a video threshold); using *W* or *L* illumination tilted at an angle of 10–30° (angular frequencies of the frost noise) and a 10° observation aperture, a negative image is obtained with good contrast and moderate noise but low resolution. (Only the random noise is then observed in the spectrum.)

D-mode: In the zero order, a high-quality spectrum is observed with *L* but the image, positive, visible with *W*, requires phase-contrast methods for *L* reconstruction; the +1 or -1 orders give a high-quality negative image (amplitude modulated) with *L* or *W*, but low-pass filtering is observed in the spectrum slightly above the carrier frequency.

More detailed experiments and a tentative interpretation will be published soon. So far the imaging capabilities can be demonstrated by the following pictures which are reconstructions from double-exposure recordings *D*. The high resolution and contrast are illustrated by the coherent reconstruction of a spoke target (+1 order, yielding a negative image) shown in Fig. 1. Investigations with a microscope reveal that contrast inversions introduced by slight defocusing during the recording can be observed up to the highest spatial frequencies of the target ($\sim 100 \text{ mm}^{-1}$). The poor quality of the film translation system and the protection against dust are responsible for avoidable scratches on the images. The dynamic range was evaluated using a photographic step tablet (with 0.15 density steps) as input and performing density measurements on photographic records of the reconstructed images. After correcting for the response of the photographic film, the results can be summarized:

H-mode: Input density range of 1.25*D* (density units);

calculated contrast index of ~ 0.8 with *L* or *W* reconstruction.

D-mode: Input density range reduced to 1*D*; equivalent contrast of 1.4–1.7 with *L* illumination and 1–1.3 using *W* light.

In the last case, the lower contrast was achieved by using a third exposure to provide a proper bias: this results not only in the sensitivity enhancement observed by Saito¹⁴ but also improves the linearity of the intensity response. For the halftone image of Fig. 2, which was not optimized, the calculated contrast index is ~ 1.3 . (The input was a photographic negative.) The existence of a zero-order spectrum in the reconstruction from the *D* mode is demonstrated by Fig. 3(a) showing the spectrum of a screened image (recorded from a positive screened slide) with frequency components of 70 mm^{-1} along the diagonal axes. (The spatial carrier for the fringe exposure on the thermoplastic was horizontal.) The low-pass filtering above the spatial carrier mentioned for the +1 order is illustrated in Fig. 3(b) showing the spectrum around the +1 order of the carrier from the same recording. Narrowband filtering of the same recording was necessary to reconstruct from the zero order the image shown in Fig. 4 (which is positive as the input slide). No filtering was necessary with *W* light or to reconstruct the negative images from the first order as shown in Fig. 2 (recorded from a photographic negative) or Fig. 1.

Although projected transparencies were used here for simplicity, these double-exposure experiments demonstrate the feasibility of using thermoplastic film as an optically addressed light valve. The memory of the device permits use of a modulated writing beam from a laser scanner for recording time signals. The "snapshot" addressing technique¹⁵ can also be used since exposure of the thermoplastic is a fast electrostatic discharge process. The double-exposure technique also makes possible continuous operation of the device with film transport between separate stations for recording the image and the carrier grating and simultaneously reconstructing the images (with a time delay of one recording cycle that can be shortened to some tens of milliseconds) for incoherent or coherent real-time signal processing.

The authors would like to thank J. Schörner and the German company Rottenkolber for technical assistance and the loan of the holocamera. Contributions of the French companies Sneap and Sopra, with the participation of E. de Bazelaire and R. Stehlé in the experiments, are also gratefully acknowledged.

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