On the wavefront distortion in holograms recorded in thermoplastic films

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This letter analyzes the quality of reproduction of holograms recorded in thermoplastic media as a function of the variations in coating thickness of the different layers. The fidelity of reproduction is investigated by means of a phase sampling interferometric technique. It is found that the distortion depends on the processing parameters. A criterion for the optimization of the coating thickness of the layers is given. © *1995 American Institute of Physics.*

The recording of optical information on thermoplastic–photoconductor films is well known.[1–3] The steps of the recording process are: sensitization by means of a corona discharge device, exposure to one or more light beams and development by heating the thermoplastic to a temperature close to that of the glass transition. The possibility of reusing these materials makes them candidates for their usage as optical memories.[4,5]

The thermoplastic–photoconductor films consist of a transparent substrate layer on which two successive layers are coated: the first is the photoconductive layer, which typically contains poly-*n*-vynilcarbazole (PVK) doped with a certain amount of trinitrofluorenone (TNF), and the second is the thermoplastic layer that also contains PVK and TNF but with different molar ratios with regard to the photoconductive layer for appropriate operation.[6,7] In this letter we report the influence of the spatial inhomogeneities of the film layers on the quality of the beam reconstructed by a previously recorded hologram. An optical interferometric setup has been used to determine the fidelity of the beam reconstructed by a surface-relief phase grating recorded in a thermoplastic–photoconductor film.

Due to the manufacturing process of the substrate by extrusion procedures, spatial inhomogeneities are induced in the thickness of the material. The scanning of the surface of the substrate with an atomic force microscope (AFM, Model ARIS 3350 from Burleigh) reveals spatial inhomogeneities in the order of 155.9 nm with a rms value of 36.8 nm with regard to the mean value of the thickness 51.3 μm determined by means of the interference method described in Ref. 8. The area scanned was 35×35 μm^2. A three-dimensional plot of the AFM image is shown in Fig. 1(a). The height variations are 5 times less than the typical wavelengths λ used for the recording of holograms, thus the phase of the reconstructed beams will be spatially modified. In the same way, the inhomogeneities of the photoconductive layer could alter the dynamical behavior of the thermoplastic film; during the sensitization step, nonhomogeneous areas of surface charge density will be produced in the vicinity of the spatial inhomogeneities causing additional tangential stresses during the heating process. Figure 1(b) shows an AFM image of the top of the photoconductive layer covering a surface area of 14×14 μm^2: it reveals holes of about 130 nm in diameter and 400 nm in depth. The inspection of the top of the film, the thermoplastic layer, shows height variations in the order of 285 nm [see AFM image in Fig. 1(c)].

The alteration of the optical path by one of the layers of the film $\Delta(x,y)$ can be written as

$$\Delta(x,y)\approx\Delta[n'(x,y)h(x,y)], \tag{1}$$

where x and y are coordinates in the plane of the layer, $n'(x,y)$ is the refraction index of the layer that could be spatially inhomogeneous, and $h(x,y)$ is the height variation with regard to the average thickness of the layer considered. The overall alteration of the optical path, $\Delta_g(x,y)$, is the sum of the contributions of each layer, and its mean value

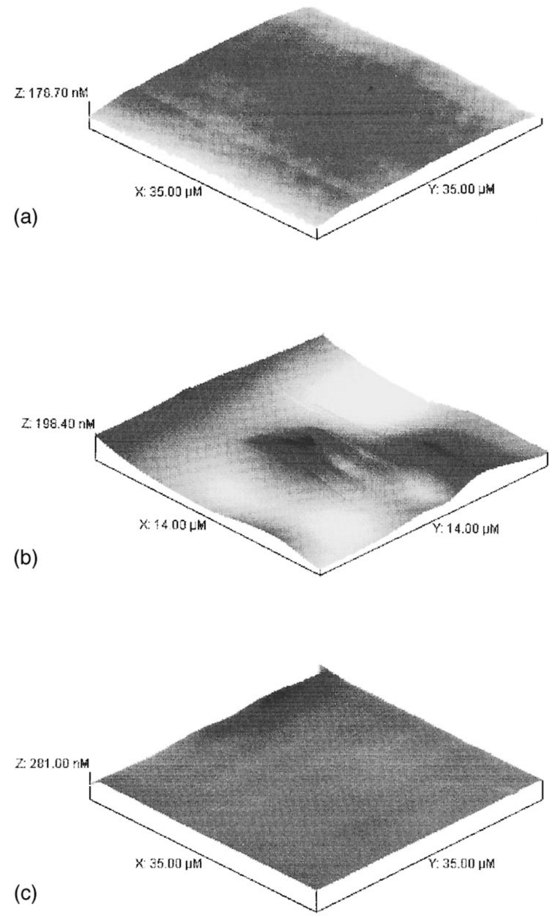

FIG. 1. (a) AFM image of the substrate commonly used in thermoplastic films. (b) AFM image of the PVK-TNF photoconductive layer used in the thermoplastic film studied. (c) AFM image of the PVK-TNF thermoplastic layer used in the thermoplastic film studied.

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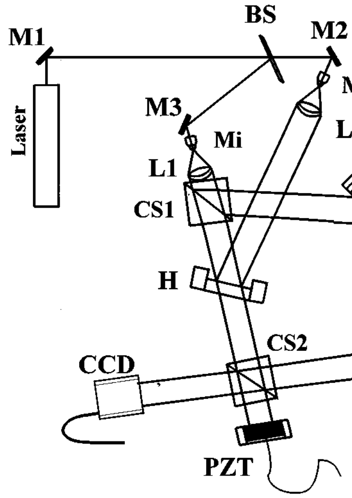

FIG. 2. Experimental setup used to measure wavefront distortion. M1, M2, M3, M4, and M5 are mirrors; L1 and L2 are the collimating lenses; Mi are the microscope objectives; H is the holographic camera.

$\langle \Delta_g \rangle$ can be considered as a parameter of the quality of the film. We remember here that the first-order diffraction efficiency η of a sinusoidal thin grating is proportional to[6]

$$\eta = J_1(\phi)^2, \neg \tag{2}$$

where $\phi = 2\pi(n-1)d/\lambda$, n being the refraction index of the thermoplastic layer and d the peak-to-peak value of the surface-relief phase grating. Let us define a quality parameter of the reconstructed beam, Q, as the relation between the phase shift produced by the grating and the phase alteration produced by the inhomogeneities. Taking into account Eq. (1) Q can be written as

$$Q = \frac{(n-1)d}{\langle \Delta_g \rangle}. \tag{3}$$

We now consider the experimental measurement of the distortion of the wavefront by means of an optical method. The holograms are recorded on a thermoplastic–photoconductor film using a commercial holographic camera (Steinbichler Optotechnik GmbH): this camera allows the control of the corona voltage applied during the sensitization of the film and the heating power applied. Figure 2 shows the experimental setup employed in our experiment: a p polarized He-Ne laser, $\lambda = 632.8$ nm, is divided by a variable beam splitter, BS, producing the reference beam, Σ_r, and the object beam, Σ_o. The angle between Σ_r and Σ_o was selected to be 32° producing an interferogram with a spatial frequency of 830 lines per mm which is within the range of the maximum diffraction efficiency of the film (see Ref. 6 for more details on the recording geometries and processing of the holograms). An electromechanical shutter allows us to select the exposure time. The use of the element BS allows the control of the modulation, i.e., the relation between the power of the reference beam and the power of the object beam. Both beams are collimated using achromatic lenses, 25 mm in diameter. The object beam is further split by a nonpolarizing cube beamsplitter CS1 (with an aperture of 50 mm): the direct transmitted beam, Σ_{o1}, impinges on the film and produces an interference pattern with the reference beam, whereas the other beam, Σ_{o2}, is directed by appropriate mirrors to another nonpolarizing cube beamsplitter CS2, whose aperture is 50 mm, for later processing. The film is exposed to both beams after sensitization in dark conditions, and heated appropriately. After development, the film is illuminated with the reference beam whereas the beam Σ_{o1} is interrupted by an opaque screen. The first-order diffracted beam, Σ_{+1}, impinges on CS2 and is combined with Σ_{o2} producing a low spatial frequency interference pattern recorded with the aid of a CCD camera (Sony Model AVC-DSCE) with the automatic gain disconnected. An image processing board is used to acquire the images of the interference pattern and transfer them to a computer. A mirror mounted on a PZT scanning actuator allows the introduction of known increments of the phase of the beam Σ_{+1}. A four-bucket technique is used to get the phase map module 2π.[9] All the system is allocated in a mechanically isolated table. All the experiments have been carried out using a corona voltage of 14 kV at 21 °C and a relative air humidity of 66%. The power of the reference beam Σ_r was 128 μW/cm^2 and the power of the object beam Σ_{o1} was 52 μW/cm^2, the exposure time being 20 ms. The heating power applied was 5.46 J/cm^2.

Before recording any hologram the film is removed and the phase map module 2π of the interferometer is acquired and stored in the computer. Allow $\phi(x,y)$ to be the phase map module 2π (reference phase map) produced by Σ_{o1} and Σ_{o2}, x and y being coordinates on the plane of the film. Allow $\phi'(x,y)$ be the phase map module 2π produced by Σ_{+1} and Σ_{o2} when the object beam is interrupted, thus the overall wavefront distortion, $\Delta_g(x,y)$ can be easily computed by subtracting both phase maps

$$\Delta_g(x,y) = \phi'(x,y) - \phi(x,y). \tag{4}$$

The phase map given by Eq. (4) includes distortions caused by problems arising from materials used such as cosmetic defects, nonlinearities in the recording process and losses due to absorption. Figure 3(a) shows the reference phase map module 2π and Fig. 3(b) shows the phase map produced by Σ_{+1} and Σ_{o2}. After subtracting the reference phase map we obtain the phase map shown in Fig. 3(c). In this latter phase map, it can be observed that there is only one fringe, i.e., there are no phase discontinuities, and therefore there is no need to use a phase unwrapping algorithm to get the complete phase map. We conclude that the distortion of the wavefront is less than λ/2 (the sensitivity of the interferometer), with small spatial variations. The experiment was conducted for different heating power ranging from 4 to 5.65 J/cm^2, i.e., from underdevelopment to overdevelopment conditions, respectively. We observed that, when modifying the heating power from underdevelopment to overdevelopment, spatial distortion greater than λ can be produced. Figure 3(d) shows the phase map $\Delta_g(x,y)$ for a heating power of 4.35 J/cm^2: there are three discontinuities in the phase map and there are points where one fringe is broken into two fringes. In the left-hand side of Fig. 3(d) the phase map produced by Σ_{+1} and Σ_{o2} has low modulation thus the distorted phase map $\Delta_g(x,y)$ nearly coincides with the reference phase map

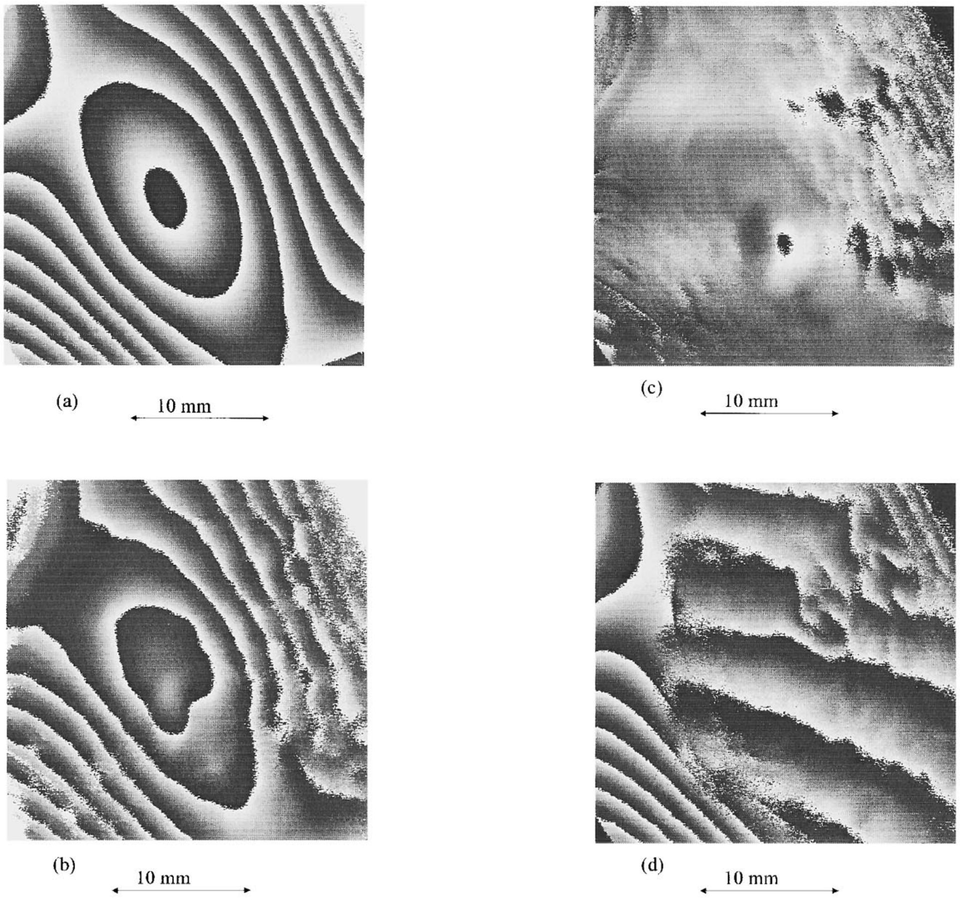

FIG. 3. (a) Reference phase map module 2π of the interferometer $[\phi(x,y)]$. (b) Phase map module 2π using the first order reconstructed beam, $\phi'(x,y)$. (c) Wavefront distortion of the first order reconstructed beam, $\Delta_g(x,y)$. Heating power applied for the development was 4.63 J/cm^2. (d) Wavefront distortion of the first order reconstructed beam, $\Delta_g(x,y)$. Heating power applied for the development was 4.35 J/cm^2.

$\phi(x,y)$. It becomes clear that heating power is a critical parameter for the optimum reconstruction of a wavefront.

Figure 4 shows an AFM image of the grating recorded. The film must be discharged before the measurement with the AFM since after the recording of the holograms there remains a small number of surface charges at the top of the thermoplastic layer. The inset shows a line of the grating recorded: the inhomogeneities in the profile of the grating, d, arise from the spatial inhomogeneities of the top of the thermoplastic layer. The value of the Q parameter given by Eq. (3) for the film considered in this work can be computed from the data of Figs 3(c) and 4, taking $n=1.5$ for the thermoplastic, the result being $Q=0.6$.

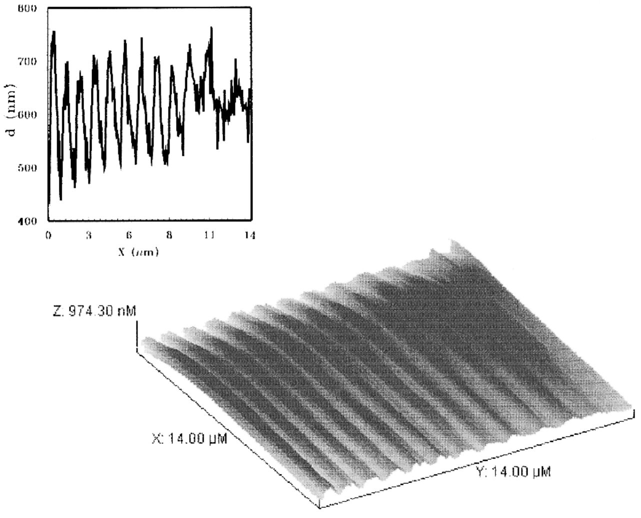

FIG. 4. AFM image of the grating recorded in the film considered.

Equation (3) gives a criterion for the design of the thermoplastic film when fidelity in the reconstruction is required.

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