Speckle Noise in Holographic Recording

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We describe the effect of speckle noise in the recording of holographic gratings. The speckle pattern appears superimposed to the interference fringes and is caused by the laser light scattering in optical components of the holographic setup. This effect is particularly important when the holographic grating, recorded first in photoresist films, is used as a mask to transfer the pattern to substrates with high reflectivity. We show that in such cases, even high quality commercial mirrors may produce serious damage in the recorded grating

Neste trabalho é descrito o efeito do ruído produzido por "speckle" na gravação de redes holográficas. O padrão de "speckle" aparece superposto às franjas de interferência e é causado pelo espalhamento da luz coerente nos componentes ópticos da montagem holográfica. Este efeito é particularmente importante quando a rede gravada na fotorresina é usada como máscara para transferência destes padrões para substratos de alta refletividade. É mostrado que nestes casos, mesmo espelhos comerciais de alta qualidade, podem causar sérios problemas na rede gravada.

1. Introduction

The holographic recording in photoresist films is widely employed to produce masters for replication of most of commercial holograms ("Benton" type [1]) and of diffraction gratings. This technique may be used also associated with reactive plasma etching to produce new types of diffractive optical components [2-3] or deep high spatial frequency structures for recording of quantum wires or quantum dots [4].

The quality of the recorded pattern depends on the several parameters such as quality of the photoresist film, substrate surface and of the interference pattern itself. The interference pattern depends strongly on the optical setup. The quality of interfering wavefronts determines the distortion of the grating lines. This distortion, however, is significant only for a great number of periods of the grating producing a low spatial frequency noise that does not disturbs significantly the diffraction properties of the components. Small defects, however, are more critical because they are of the same order of magnitude of the grating period and its angular diffraction spectrum convolutes with that of the diffraction grating [5].

Laser speckle is a well known phenomena caused by the scattering of laser light in rough surfaces. Although speckle may be a problem in experiments using laser light beams, it may be used to measure the roughness of surfaces and their movement in a large variety of applications [6]. In order to avoid speckle, the optical surfaces in holographic set-ups must be dust free and without small defects such as digs and pits. In this paper, we shown that even when high quality optical surfaces were used, the speckle effect could cause serious damage to the holographic recording.

2. Holographic recording and speckle pattern

Holographic structures may be recorded directly in the photosensitive materials or in photoresist films and then transferred to the substrate using the photoresist pattem as a mask. If the recorded optical modulation is approximately linear with the light intensity, a variation in the light intensity is converted in the same relative variation of the optical modulation. Transference processes, however, may be strongly non-linear and small variations in the light pattern could be extremely amplified. This effect is worst for high reflectivity substrates due to the reinforcement of the light pattern. Fig. 1 shows an example, in which very thin photoresist residues block the etching of the substrate due to the high selectivity of the reactive ion etching process.

Analyzing the recorded sample using smaller magnifications we observe a structure similar to a speckle pattern as it can be seem in Fig. 2a and 2b.

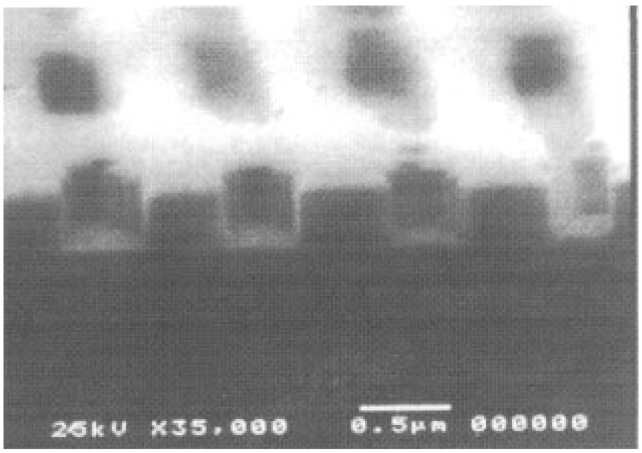
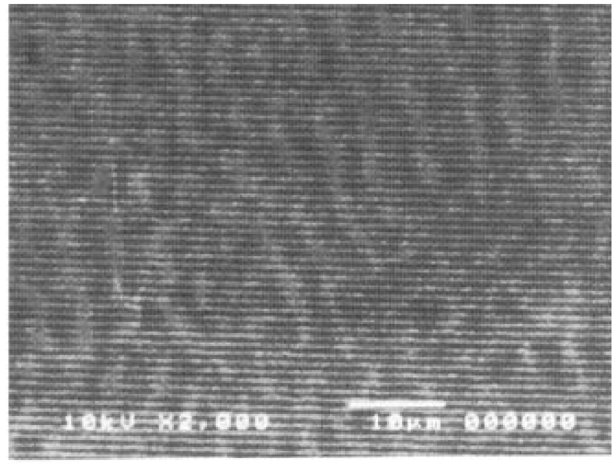


Figure 1. Grating of 855 nm of period transferred to amorphous carbon hydrogenated (a-C:H) film by reactive ion etching, using an Al mask recorded by holographic exposure of a photoresist film.

In our holographic set-up, the unique possible source of speckle are the last two collimating mirrors, because the expanded light beams are spatially filtered just before them. The collimating mirrors have focal length of 1 meter, with 100 mm of diameter, were made in low expansion borosilicate glass (LEBG), with surface accuracy $\lambda/10$ at 546 nm and were coated with protected aluminum. The optical quality of the surface stated by the manufacturer is 60-40 scratch and dig.

If the speckle generated in the mirror roughness produces the grating noise, the speckle grain size should depend on the mirror aperture. Fig. 3 shows a schema of the speckle generated in the plane O' due to the laser scattering in the roughness surface O.



(a)

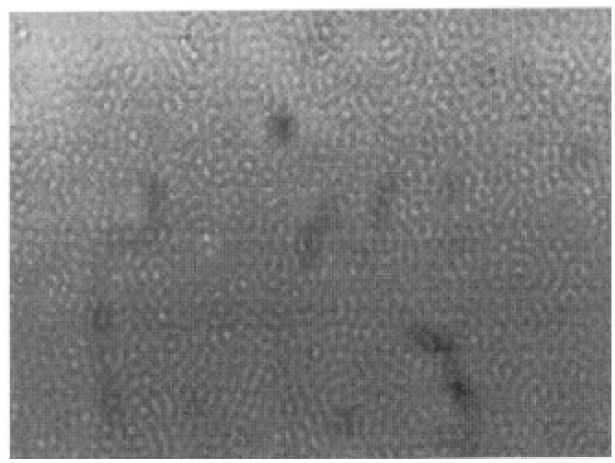


Figure 2. Micrographs of a grating of period 855 nm recorded in photoresist and transferred to the Al film by chemical etching: (a) magnification of 2000 X (SEM microscope) and (b) magnification of 500 X (optical microscope)

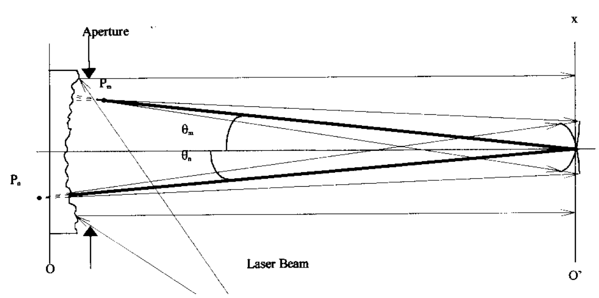


Figure 3. Speckle generation in the plane O' produced by a roughness surface in O.

The light intensity in O' is described by the relation bellow [7]:

$$I(x) = \sum_{n=1}^{N} \alpha_n^2 + 2\sum_{n=1}^{N}\sum_{m=n+1}^{N} \alpha_n\alpha_m \cos[kx(\sin\theta_n - \sin\theta_m) + (\phi_n - \phi_m)] \quad (1)$$

Where:

$\alpha_{m,n}$ are the amplitudes of the waves arriving at O', and x is a lateral displacement in the plane O', $\phi_{m,n}$ are the arbitrary phases of each interfering waves and the angles $\theta_{m,n}$ are the central angles between the waves (as indicated in Fig. 4). The period of the interference fringes is given by:

$$\Lambda = \frac{\lambda}{(\sin\theta_n - \sin\theta_m)} \quad (2)$$

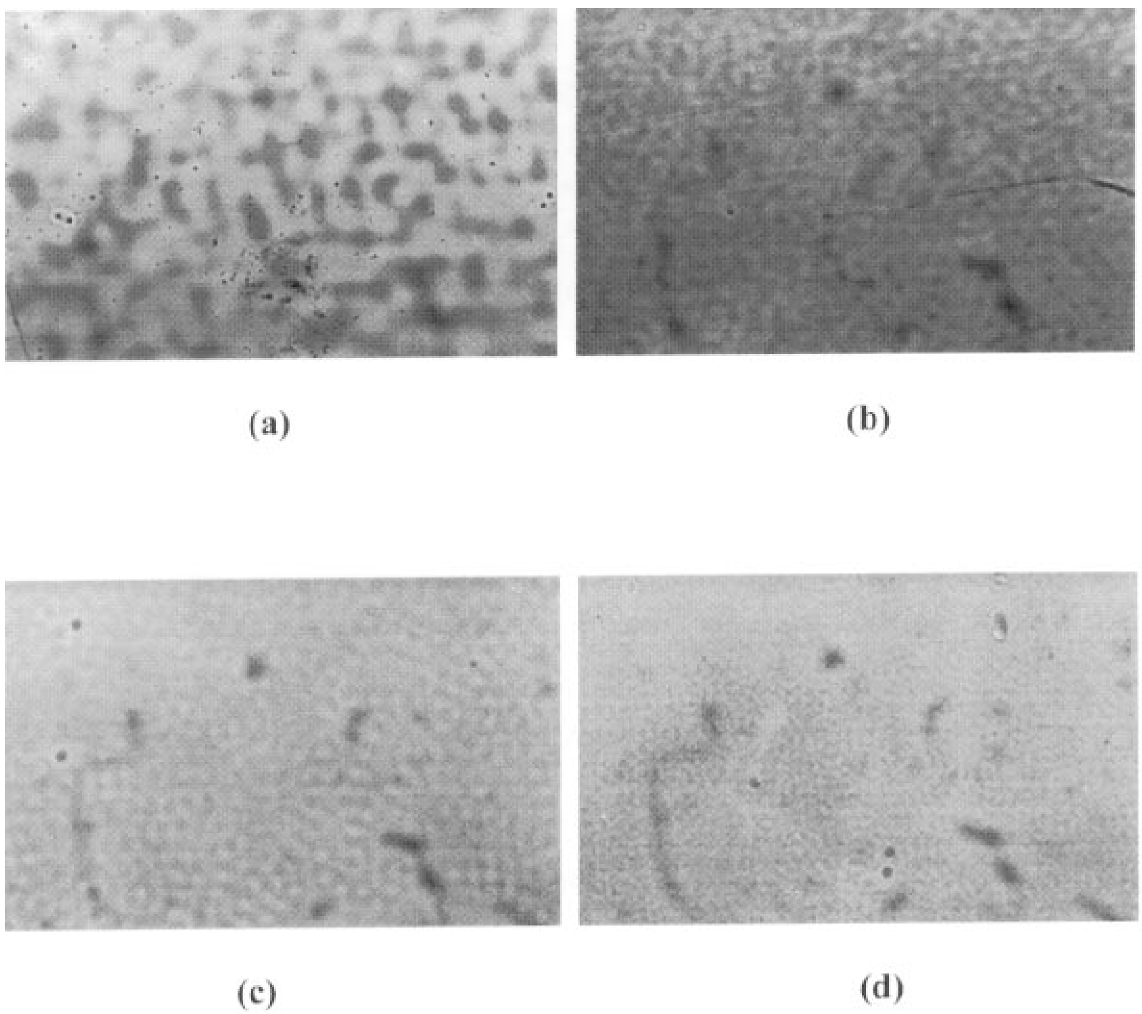


Figure 4. Speckle patterns generated by the mirrors, photographed by an optical microscope, for different apertures ϕ: (a) ϕ = 10mm, magnification 100X; (b) ϕ = 20mm, magnification 100X; (c) ϕ = 50mm, magnification 200X; and (d) ϕ = 90mm, magnification 200X.

The minimum size of the speckle grain corresponds to the minimum period Λ_{min} of the interference fringes. This minimum period Λ_{min} is determined by the largest angle between the interfering waves; $(\sin\theta_n - \sin\theta_m) = 2\sin\theta_{max}$, with $\sin\theta_{max} \cong \phi(2z)$ the maximum aperture in O, ϕ = mirror diameter and z = the distance between O and O' (mirror and hologram).

$$\Lambda_{min} = \frac{z\lambda}{\phi} \tag{3}$$

In order to check the speckle origin of this noise we recorded several gratings using different mirror's apertures. The results are shown in Fig. 4a, b, c, d.

As it can be seen from the Fig. 4 there is a clear dependence on the sizes of the grains with the aperture. In Table l we show an evaluation of the minimum grain sizes (Λ_a), measured from the photographs in comparison with those calculated (Λ_c) using the relation (3) and the aperture values (ϕ).

3. Conclusions

The measured grain sizes (shown in Table l) are slightly greater than the minimum calculated sizes. This occurs probably because, due to the small sampling of the photographs, the measured grain sizes correspond to an average and not to the smallest grain size. The linear dependence with the aperture size, however, confirms that the noise observed in recorded gratings was caused by the speckle in the collimating mirrors.

Table 1 - Speckle Sizes

ϕ (mm)	10	20	50	90
Λ_a (μm)	24 ± 5	14 ± 3	7 ± 1	2.7 ± 0.5
Λ_c (μm)	20 ± 2	10.0 ± 0.5	4.0 ± 0.1	2.23 ± 0.05

There are many possibilities for reducing this speckle noise in the recorded gratings or holograms. The simplest one is to change the collimating mirrors for better quality mirrors. This solution, however, is very expensive because there are not commercial concave mirrors with better quality and they must be specially ordered. The other possibility is to blur the spatial coherence, by using a rotating diffuser. This solution, however, requires a precise adjustment in the optical path difference between the interfering beams in order to remain the temporal coherence.

In order to reduce the noise of our gratings we are using a different method that is based on the nonlinear processing of the photoresist. If the photoresist is developed in strong non-linear conditions, the sinusoidal interference light pattern may be converted in a rectangular profiled grating in the photoresist. In such condition small variations in the amplitude of the photoresist grating (produced by any type of noise) do not change the line widths of the gratings.

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