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Numerical aperture increasing in digital holography by a two-dimensional grating

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***Abstract* - We show how it is possible to increase synthetically the numerical aperture of an interferometric imaging system using a 2D diffraction grating, thus improving the spatial resolution of the reconstructed images up to three times.**

I. Introduction

Digital Holography (DH) provide coherent imaging in microscopy for a variety of applications such as characterization of silicon MEMS, three dimensional imaging [1], particle image analysis [2]. The potential applications of DH have been extended to a wide spectral range, from far IR [3] to deep UV [4]. The computational image reconstruction from a digital hologram has many advantages compared to the traditional optical holography, including amplitude and phase imaging, 3D imaging and the digital wavefront manipulation. On the other hand, some disadvantages also exist. In fact, no electronic device is able to compete with the high resolution (up to 5000 lines/mm) of the photographic emulsions used in optical holography. Therefore, in most cases, the resolution achieved in DH is too low and not qualified for practical applications.

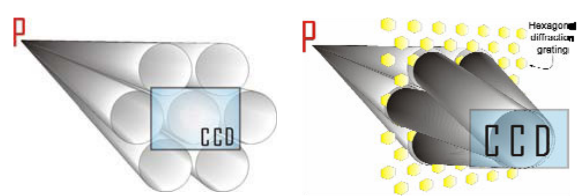
Recently, important results have been achieved for increasing the numerical aperture and therefore the optical resolution in DH imaging. In fact, because of the finite aperture of the imaging system, only the low frequency parts of the object spectrum are transmitted and then recorded by the sensor. Therefore, the corresponding reconstructed images are band limited in the frequency domain. Different approaches have been tested to increase the NA of the optical system in order to get super-resolution. Massig et al. increased the NA by recording nine holograms with a camera (CCD array) translated to different positions and by recombining them in a single synthetic digital hologram [5]. Alexandrov et al. were able to break the diffraction limit by rotating the sample and recording a digital hologram for each position in order to capture the diffraction field along different directions [6]. Here, we propose a different method based on the use of a diffraction grating to obtain super-resolved images [7,8]. Essentially, the technique allows to collect parts of the spectrum diffracted by the object, which otherwise would fall outside the CCD array. This was achieved by inserting in the recording DH set-up a diffraction grating. Basically, three digital holograms, for each diffraction direction, are recorded and spatially multiplexed onto the same CCD array. Super-resolved images can be obtained by the numerical reconstruction of those multiplexed digital holograms, by increasing up to three times the NA along each diffraction direction.

The grating we use is a 2D hexagonal phase grating that allows to obtain super-resolution in two dimensions along three different directions.

II. Experimental Set-up and Numerical Reconstruction Technique

The recording process was carried out by using a Fourier configuration in off-axis mode. The laser source is a He-Ne laser emitting at 632nm. The CCD array has (1024 × 1024) pixels with 7.6 micron pixel size.

The diffraction grating G is inserted in the optical path between the object and the CCD. The diffraction grating consisted of a 2D array of hexagonally shaped periodic reversed domains in a lithium niobate (LN) substrate with a pitch of 35 μm. After poling, transparent ITO (indium tin oxide) electrodes were deposited on both *z* faces of the sample in order to apply an external field across the crystal preserving the optical transmission along the *z* axis. The phase step between opposite ferroelectric domains can be varied by changing the applied voltage across the *z*-axis of the crystal. When no voltage is applied to the crystal, no diffraction occurs. When voltage is applied, the grating becomes active (*switched-on*) and it is able to generate different diffraction orders. Essentially, each diffraction order produces a corresponding digital hologram and all of the holograms are spatially multiplexed and recorded simultaneously by the CCD.



(a) (b)

Fig. 1 Scheme of the ray diagrams of the object waves: (a) without the grating in the setup and (b) with the grating in the setup.

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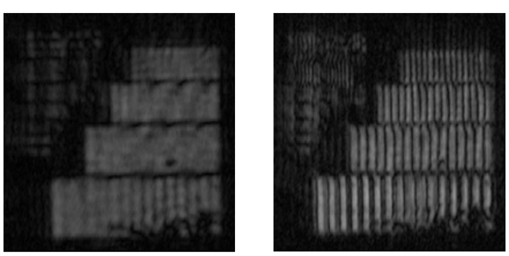
The schematic view of the object waves is shown in Fig. 1(a), (b) where only one point object P is discussed. The holographic system in Fig. 1(b) clearly exhibits higher NA compared to that in Fig. 1(a). In fact, the CCD aperture augments up to three times along each of the three diffraction directions. Consequently, the reconstructed image of the point P has a resolution enhanced up to three times compared to the usual DH system without the diffraction grating.
Through the numerical reconstruction of the multiplexed hologram, the seven reconstruction coming from the different multiplexed holograms are automatically superimposed and a super-resolved reconstructed image is obtained. This is the main advantage of the proposed technique in respect to other methods used to enhance the numerical aperture, in which different multiplexed holograms are superimposed by means of difficult numerical procedures.
The numerical reconstruction of the multiplexed digital hologram was divided into two steps. In the first one the wavefield is propagated back in the plane just behind the grating. Then, this complex amplitude distribution is multiplied by the transmission function of the grating to obtain the wavefield in the plane immediately before the grating. Finally, propagating back to the object plane this complex wavefield, we obtained the final reconstructed image with the enhanced resolution. As the grating transmission function we use

$$T(x_1, y_1) = 1 + a\cos(2\pi x_1 / p) + \\ + b\cos\left(\left(x_1 + \sqrt{3}y_1\right)\pi / p\right) + c\cos\left(\left(x_1 - \sqrt{3}y_1\right)\pi / p\right) \quad (1)$$

III. Results

Figure 2a shows the amplitude reconstruction of the digital hologram acquired when no voltage is applied to the electro-optic grating, while in Fig.2b is shown the super-resolved image obtained through the proposed technique. The resolution enhances up to three times along each of the diffraction directions.



(a) (b)

Fig. 2 (a) Amplitude reconstruction of the digital hologram acquired when no voltage is applied to the electro-optic grating, (b) super-resolved image obtained through the proposed technique.

Finally, we acquired the holograms of a biological sample, formed of some slides of a fly head, whose optical microscope picture is shown in fig.3 (a)

In Fig.3(b) and 3(c) are shown the amplitude reconstructions corresponding to the holograms acquired with and without the grating.

(a)

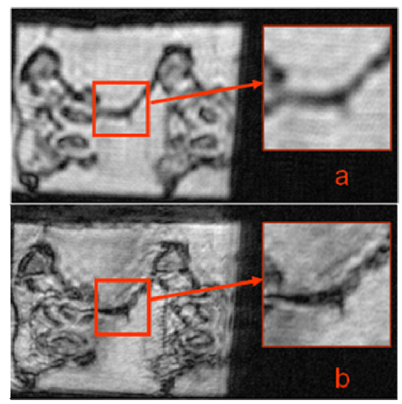


Fig. 3 (a) fly's head optical microscope image; (b) image reconstruction obtained without the diffraction grating; (c) super- resolved image obtained using the grating.

IV. Conclusion

In conclusion we demonstrate that it is possible to increase synthetically the numerical aperture of an interferometric imaging system using a 2D diffraction grating, thus improving the spatial resolution of the reconstructed images up to three times along each of the diffraction directions.

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