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Digital holographic microscopy with photorefractive sillenite $Bi_{12}SiO_{20}$ crystals

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ABSTRACT

In this work, we demonstrated by first time that image digital holographic microscopy can be instrumented using photorefractive sillenite $Bi_{12}SiO_{20}$ (BSO) crystals in diffusion regime as holographic recording medium. The writing–reading holographic process in photorefractive BSO crystal and this holographic reconstructed image is combined to form the image hologram with the second reference beam in CCD plane in the Mach–Zehnder interferometer. The system was tested using a micro scale object and 3D phase image is calculated by performing digital reconstruction using only one hologram.

1. Introduction

In digital holography by calculating the complex optical field of an image, the amplitude and phase of the optical field are available for direct manipulation [1–4]. The applications of digital holography to microscopy are particularly advantageous because a single hologram records the information of a three-dimensional object space. These advantages have been noted since early in the development of digital holography and applied to imaging analysis of microstructures and biological microscopy [5,6] using CCD as hologram detector. In off-axis holography the angle of incidence of the reference beam is chosen so that when the hologram is reconstructed, the zero order light may be spatially separated from the diffracted holographic reconstruction. The method of off-axis holography involves a high spatial-frequency fringe pattern that must be sufficiently sampled by the CCD, in which case the spatial resolution of the CCD is an important parameter.

On the other hand, the photorefractive crystals have been used as holographic recording medium in many holographic applications with optical image reconstructions [7,8] and phase-shifting techniques application using digital interferograms [9–15]. Several works reported the employ of photorefractive crystals (PRCs) in holographic interferometry throughout the last decades, since many interesting properties qualify them as recording media for real-time holographic interferometry (RTHI) [9–13]. The light-induced mechanisms that characterize the holographic grating build up in these crystals are the photorefractive effect, the thermo-optic refractive index modulation and the photochromic effect [16–18]. The first effect consists on the refractive index modulation through photo-induction and linear electro-optic effect (Pockels effect); the refractive index modulation by thermo-optic effects is due to temperature gradients on the crystal surface; the latter effect is caused by absorption coefficient modulation for high light intensities.

These holographic recording materials present advantages like high spatial resolution, indefinite reusability and *in situ* self-processing of recording medium. Photorefractive crystals of the sillenite family such as $Bi_{12}SiO_{20}$ (BSO), $Bi_{12}TiO_{20}$ (BTO) and $Bi_{12}GeO_{20}$ (BGO) particularly present very interesting properties for RTHI. Despite their lower gain if compared with other materials like $BaTiO_3$ and $LiNbO_3$, they present a much faster hologram build up and provide less noisy holographic images due to their anisotropic diffraction properties, through which the transmitted object wave is cut-off thus enabling the readout of the diffracted wave only [7]. Those properties enabled studies on vibration analysis, stress and deformation measurement, and material characterization. Many works contributed to the field of holographic interferometry by phase-shifting methods with photorefractive crystals [9–13]. Spatial phase measurements are basically accomplished by changing the interferogram intensity. The phase shifting process consists on the acquisition of many interferograms which have their intensities changed by continuous, linear mirror micro-displacements [14,15].

More recently, Zhao et al. [16] used digital holography with Mach–Zehnder interferometer and CCD camera for refraction index change determinations in photorefractive crystals using

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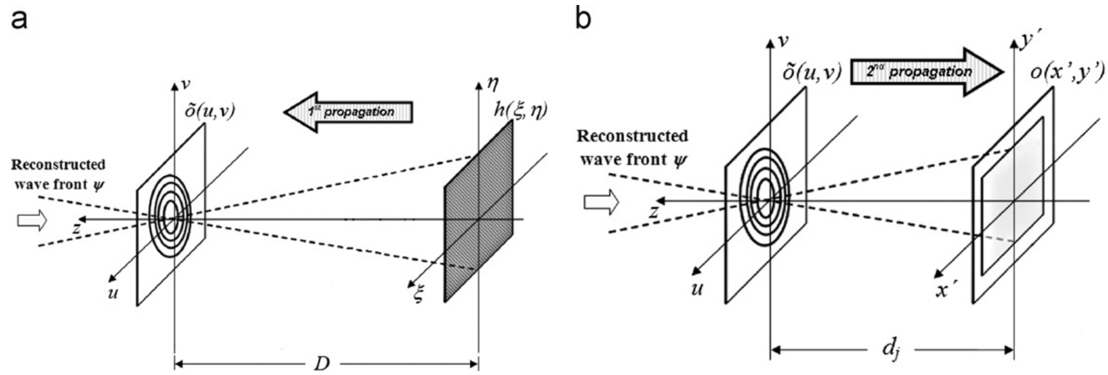

Fig. 1. Double propagation method for image reconstruction.

two holograms (with and without crystal illumination) as usual in holographic interferometry. de Angelis et al. [17] studied photorefractive crystals characterization by means of reflection experimental setup for holograms registration based on interferometric techniques; the numeric reconstruction was made using the Fresnel transformation method.

But until now, the photorefractive crystals had not been used for digital holographic microscopy with direct phase image reconstruction. In this work, we show, by first time in our knowledge, the possibility of using photorefractive $Bi_{12}SiO_{20}$ (BSO) crystal in diffusion regime as holographic recording medium for digital holography microscopy with digital direct phase image reconstruction using a Mach–Zehnder interferometer for the second hologram registration.

2. Theoretical considerations

2.1. Holographic recording process in photorefractive $Bi_{12}SiO_{20}$ crystal

In photorefractive holography (PRH) using BSO crystal recording medium, the holographic recording occur by a refractive index modulation, $\Delta n = -\frac{1}{2} n^3 r_{41} E_{sc}$, via photorefractive effect in diffusive regimen and the holographic reconstruction of the object wavefront occur quasi simultaneously, where the optical reconstruction of the holographic image is in diffracted wave. If λ is the recording wavelength, ρ is the crystal rotatory power, L is the crystal thickness, m is the modulation of the incident interference pattern and 2θ is the angle between the interfering beams, the diffraction efficiency of a hologram grating recorded in a photorefractive crystal by diffusion is given by [11–13]

$$\eta = \left(\frac{\pi \Delta n}{\lambda \cos\theta}\frac{\sin \rho L}{\rho L}\right)^2 m^2 \quad (1)$$

The intensity I_0 at a point (x, y) resulting from the superposition of the diffracted and the transmitted waves is given by [18–20]

$$I_0(x,y) = I_{0,T}(x,y) + I_{0,D}(x,y)[1-e^{(-t/\tau)}]^2 \quad (2)$$

where τ is the hologram response (writing or erasure) time and $I_{0,T}(x, y)$ is the transmitted object wave. The holographic reconstruction of the object wave, $I_{0,D}(x,y)$, is written as [18],

$$I_{0,D}(x,y) = I_{0,O}(x,y)\eta + I_{0,R}(x,y)[1-\eta] + 2g\,\Upsilon\cos\Delta\Phi \quad (3)$$

were $I_{0,O}(x,y)$ and $I_{0,R}(x,y)$ are object and reference beam intensities, respectively, g is a parameter of the polarization coupling of beams, $\Upsilon \equiv [\eta(1-\eta)I_{0,O}(x,y)I_{0,R}(x,y)]^{1/2}$ is the interference term and $\Delta\Phi$ is the phase shift on the object beam.

Usually, in photorefractive holographic interferometry for phase determination is applied the phase-shifting technique [9–13], the phase interferogram is calculated using intensities interferograms for what a sequence interferograms is captured. Before each interferogram to be captured a known change of phase in the reference beam is introduced. The four-frame technique uses four interferograms to determine the phase at each point (i, j). By capturing four $\pi/2-$ phase shifted interferograms the phase map can be obtained [14]. The intensity of the n-th interferogram $I_{0n}(x,y)$ is given by,

$$I_{0n}(x,y) = I_0(x,y)\cos^2\left[\Delta\Phi(x,y) + \frac{(n-1)\pi}{2}\right], \quad n = 1, 2, 3 \text{ and } 4 \quad (4)$$

In 4-frame phase-shifting technique the wrapped phase map is calculated with the help of the equation below

$$\Delta\Phi(x,y) = \arctan\left[\frac{I_{04}(x,y)-I_{02}(x,y)}{I_{01}(x,y)-I_{03}(x,y)}\right] \quad (5)$$

This calculation results in a wrapped phase map where the 2π jumps can be removed through unwrapping methods [15].

2.2. Holographic reconstruction process by digital holographic microscopy

For digital reconstruction, we will use the double propagation method [21] which consists two steps for wavefront reconstruction, the first propagation from the hologram plane until the lens focal plane ([22], Fig. 1(a)), later on the complex amplitude of the diffraction pattern in this plane is calculated and it is done a new propagation process until the image plane (Fig. 1(b)).

This method let to do the image reconstruction beginning from holograms focused in the CCD plane or out of it and with only one hologram the phase field with curvature correction caused by the microscopic objective is calculated. For the experimental application it is programmed in the reconstruction and processing software HOLODIG [23].

3. Experimental details

The optical system is described in Fig. 2. The usual Mach–Zehnder interferometer is modified for making photorefractive crystal experiments, the photorefractive holography (PRH) [7–13].

The light beam from Argon ion laser (Spectra-Physics) after passing through a beam expander SF_1 pass through a lens L_1 to correct its parallelism. An objective ($50\times$, 0.95NA) direct the image into holographic recording BSO crystal ($10.0\ mm \times 10.0\ mm \times 3.0\ mm$) which combined with the reference beam at 45° and then give the volume hologram. For the optical path compensation mirrors M1 and M4 are used. The image is optically reconstructed and then interfere with reference beam 2 producing an image hologram which will be digitalized by CCD camera (HDCE-10) and by digitally reconstruction finally the phase image is obtained. As it is known a slight angle is introduced between the object and the reference beams in the second interferometer for off-axis holography.

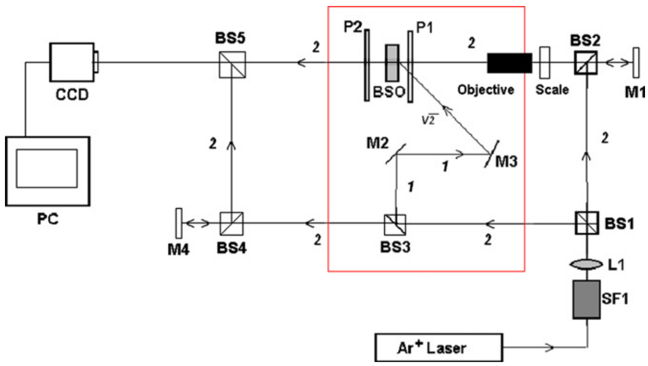

Fig. 2. Experimental setup for digital holographic microscopy with photorefractive sillenite $Bi_{12}SiO_{20}$ crystal as recording medium.

The camera uses an array of 1024×768 pixels with pixel size of 4.65 μm and 24-bit scale output. An IEEE 1394 cable connects the camera to the computer. The image reconstruction is performed by the own HOLODIG program supported in MatLab©, using double propagation reconstruction algorithms [21].

4. Results and discussions

For testing the capture system it was used a phase object using only the classical Mach–Zehnder part of the interferometer. In Fig. 3 it is shown the hologram, the intensity image and the phase image from the pure phase object with 12.5×0.35 objective, for reconstruction it was used the double propagation method (DPM) with only one hologram [21]. As can be seen the image quality is good.

The most important result is showed in Fig. 4 using an optical reticule as object and objective 50×0.95. In this configuration the photorefractive holographic recording BSO crystal is used as primary hologram detector. To obtain the hologram shown in

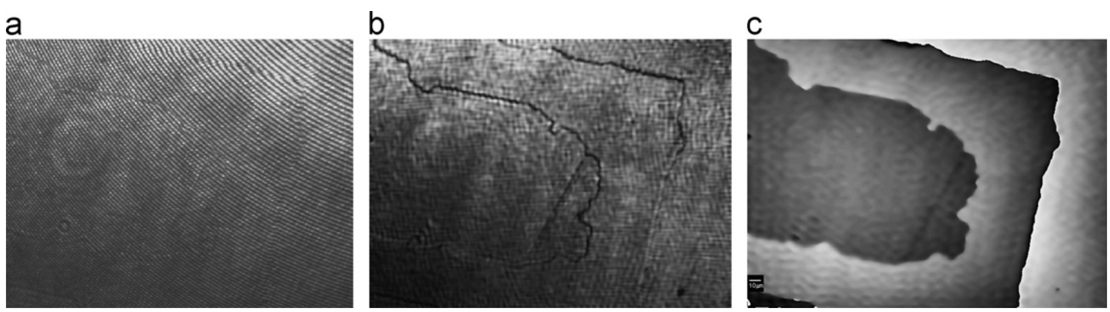

Fig. 3. Results with digital reconstruction by MDH: (a) hologram, (b) intensity image and (c) phase image.

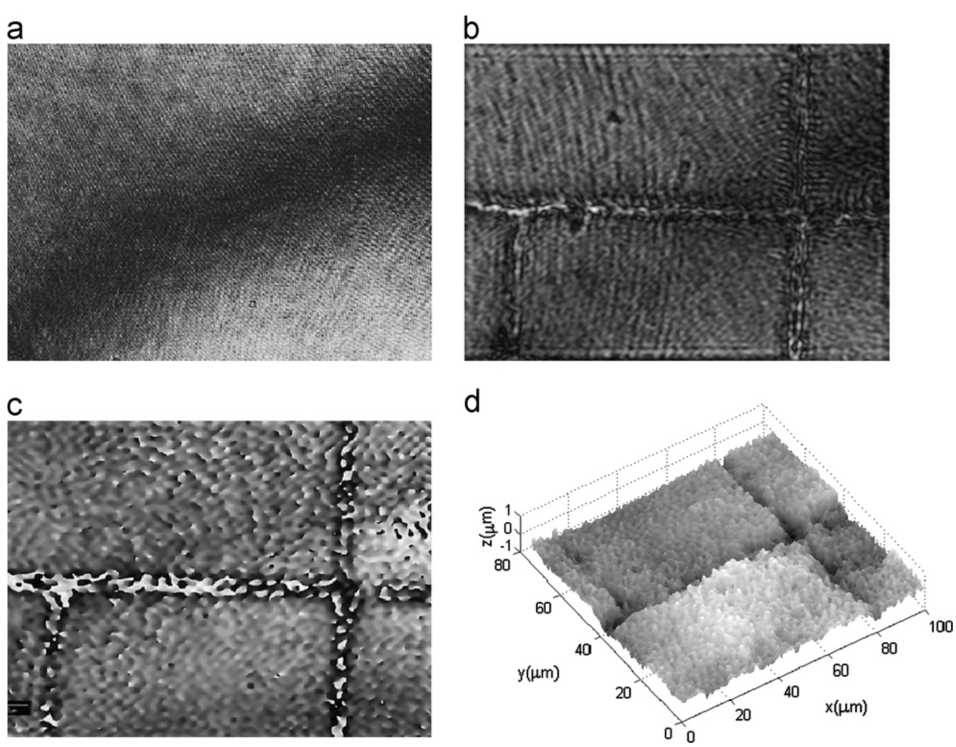

Fig.4. Results with photorefractive crystal as holographic recording medium and digital reconstruction by MDH: (a) hologram, (b) intensity image, (c) phase map, (d) pseudo 3D phase representation.

Fig. 4(a) the optically reconstructed intensity image from the crystal with the reference beam in the second interferometer was combined. The digital image reconstruction is done with DPM algorithm from the CCD Mach–Zehnder digital hologram. It can be seen the hologram in Fig. 4(a), the intensity image in Fig. 4(b), the phase image in Fig. 4(c) and the pseudo 3D phase image representation of a reticule in Fig. 4(d).

Because of crystal conditions it was not possible to obtain a more defined holograms, but as can be seen the digitally reconstructed phase image has good qualities and in spite of the superpose low frequency interference fringe and for that apparent low quality hologram, the images quality are at first time less while the same compared with that of classical digital holographic microscopy, with better crystal registration conditions, of course the reconstructed image will be better. Because of the high resolution of crystal and the amplification of the objects details the resolution power of the final image will be limited only by the resolution power of the microscopic objective used to project the image under the crystal. It should be said that the DPM used for image reconstruction is able to extract the image information, because of this algorithm uses Fourier filtering as it is fundamental principle in the Fourier plane.

5. Conclusions

As it is demonstrated here, the photorefractive crystals can be used for digital holographic microscopy with direct phase image reconstruction by taking only one hologram; usually it was used phase-shifting technique which is more complicated because of the PZT use for reference phase change required and for quantity of the holograms number. This new technique is very efficient and could be used for any other works using photorefractive crystals as hologram detector with direct phase image reconstruction and very easy image manipulation.

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