Multi-imaging capabilities of a 2D diffraction grating in combination with digital holography

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In this Letter we report on an alternative approach to get multiple images in microscopy, exploiting the capabilities of both a lithium niobate diffraction grating and digital holographic technique. We demonstrate that multi-imaging can be achieved in a lensless configuration by using a hexagonal diffraction grating but overcoming, thanks to digital holography (DH), the many constrains imposed by the grating parameters in multi-imaging with Talbot effect or Talbot array illuminators. In fact, DH permits the numerical reconstruction of the optical field diffracted by the grating, thus obtaining in-focus multiple images in a plane different from the fractional or entire Talbot ones. © 2010 Optical Society of America

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Multiple imaging has been and still is an important issue in optics. Since the 1970s a lot of work has been accomplished with the aim to produce lensless multiple imaging by using self-imaging techniques [1]. Integral imaging is another important field of investigation to get, for example, 3D imaging by picking up images along different directions by means of a lenslet array able to produce multiple imaging [2–4]. One more motivation that pushed the investigation on multiple imaging was also the advancement in microlithography to get more efficient lithographic processes [5]. Nevertheless, the Talbot effect has been deeply investigated and proposed as viable way to produce array illuminators [6,7]. More in general self-imaging, as clearly claimed by Lohmann *et al.* in a recent paper, is the way to produce images of an object in lensless configuration [8]. Self-imaging is possible for periodic or also quasi-periodic objects (i.e., the Montgomery effect [9]). The Talbot effect requires periodic objects, and images are produced at integer Talbot distances. However, also at fractional Talbot distances it is possible to get a self-imaging effect, and in fact the effect is named the fractional Talbot effect. It is important to note that sometimes the term Talbot array illuminator (TAIL) [6,10–14] is used. In fact by means of TAILs it is possible in some circumstances to obtain multiple imaging that again can be classified as a lensless imaging approach. Of course, the Talbot effect and imaging by a TAIL are correlated each other. The possibility to get multiple imaging by a TAIL offers some advantages over the use of classical optical lenses. In fact the use of a lens can be inhibited for simple reasons, such as limitation of space in the optical configuration and/or accessibility or equally well limitation in terms of aberrations or even simplification of fabrication and reduction of cost to realize low-cost optics.

In this Letter we present a method in which the combination of the multi-imaging properties of a diffraction grating and coherent imaging by means of a digital holography (DH) technique allows us to obtain multi-imaging. Use of periodic object (amplitude or phase grating) can be of some importance in microscopy. In fact the use of a grating, as recently demonstrated, can allow one to go behind the diffraction limit by means of coherent imaging methods like DH [15–17]. Using the Talbot effect with DH has also been investigated [18,19]. The results presented here show that it is possible to easily form multiple images in a lens-less configuration by numerical reconstruction, independently from the constrains imposed by multi-imaging with the Talbot effect or a TAIL approach, by combining DH with a diffraction grating. Nevertheless, multiple real images can be optically reconstructed very easily by a spatial light modulator (SLM) [20–22].

In this work we exploit the imaging properties of a lithium niobate (LN) diffraction grating and show how DH can be used to optimize the imaging properties of this device. The LN substrate allows light transmission over a wide spectral range, from the IR to the near-UV regions ($5\ \mu m - 400$ nm). The fabricated device consists of a two-dimensional (2D) array of periodically inverted ferroelectric domains, along the z axis, in an LN sample, obtained by photolithographic and electric field poling processes [23]. The pitch of this hexagonal pattern is $35\ \mu m$. After poling, the sample is wet etched to get surface structures having micrometer pitches. In fact, long etching in hot ($50°C-60°C$) hydrofluoric acid results in differential etching of opposite ferroelectric domain faces. In this way we obtain a 2D structure in which each hexagonal domain is become a truncated pyramid. Figure 1(a) shows an optical microscope image of the domains structure after poling process, while Fig. 1(b) represents a scaning electron microscope (SEM) image of the obtained sample after the etching process. The height of the microstructures is about $40\ \mu m$. The sample acts as an amplitude spatial filter (ASF), with a duty cycle of about 0.6. In fact the light is transmitted only by the top of the pyramid (whose dimension is $\approx 20\ \mu m$, see Fig. 1), whereas it is diffused by the etched grooves between pyramids. As a conventional amplitude sampling filter, it can be used for multiple imaging of input objects illuminated by monochromatic light operating in the Fresnel regime

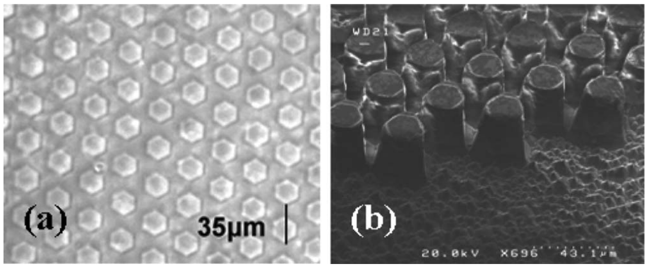

Fig. 1. (a) Optical microscope and (b) SEM image of the fabricated LN grating. The pitch of the structure is about 35 μm.

of diffraction [1]. In 1973, Bryngdal showed how a pinhole array could be used to form multiple images of the object in several planes before and after the array, which are the entire and fractional Talbot planes. Subsequently, the theory of lensless formation of multiple images from a single object has been studied in depth. It was found that a good array of images can be obtained only if some requirements, especially the duty cycle of pinhole array and the maximum possible size of the object, are satisfied [12,24].

We use the fabricated LN-based ASF for multiple image formation. To this aim a simple optical setup is used, as depicted in Figs. 2(a) and 2(b). A He–Ne laser beam illuminates a target (20 lines/mm) and afterwards goes through the LN grating, which we call LN-ASF. The distance d_1 between the target T and the LN-ASF is 75 mm, whereas the distance d_2 between the LN-ASF and the CCD is 165 mm. For the used (hexagonal) array, the Talbot distance is $Z_T = 3t_x^2/2\lambda \approx 3$ mm, where $t_x = 35$ μm is the period of the hexagonal grating and λ is the laser wavelength, which is 632 nm. To study the near-field intensity patterns, we have exploited a digital holographic method. To this aim the laser beam is split in two arms before impinging on the LN-ASF by means of a polarizing beam-splitter (PBS), according to a Mach–Zehnder interferometer configuration. Then the reference and the object beams are recombined by the beam splitter (BS) to obtain an interferogram pattern behind the BS. The fringe pattern is digitized by a CCD camera with (1024×1024) square pixels 7.4 μm sized.

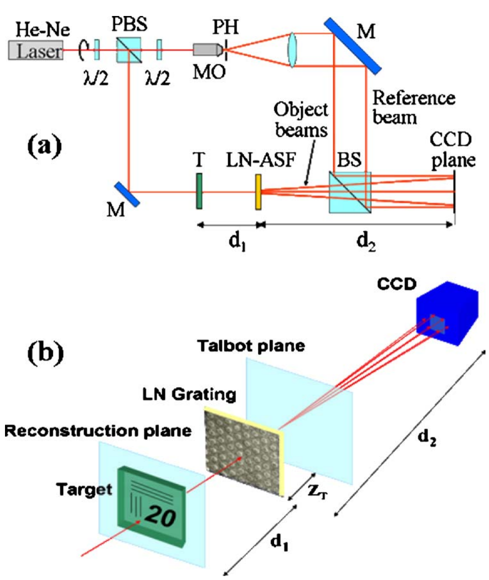

Fig. 2. (Color online) Experimental setup used for the interferometric measurements and (b) close-up of the main elements and distances.

In Fig. 3(a) a typical acquired interferogram is shown. The diffraction orders produced by the sample are clear visible. The interference fringes are superimposed onto such diffraction image as shown by the magnified view in Fig. 3(b). The fringe pattern is different for different diffraction orders because of the variation of their k vector directions. In the chosen geometry the reference beam is collinear with the zero-order of diffraction that, therefore, cannot be reconstructed because of the few present fringes. On the other hand, in this way, the fringe patterns of the first diffraction orders have all the same spatial frequency and are symmetric in respect to the optical axis of the imaging configuration. Therefore they can be reconstructed, all in the same way, without any aliasing problems. The same argument is also valid for the second diffraction orders. Of course one limitation of this method consists in having a postprocessing of digital data before getting the multiple images. So our method is not real-time but implies some delay owing to the numerical computation. Thanks to the digital holographic method we can reconstruct the wavefront back to any distance d from the CCD. We have scanned the range $[-Z_T, Z_T]$ around the LN-ASF sample. Results show that no in-focus multi-image is formed in the fractional and entire Talbot planes. For example, Fig. 4(a) shows the reconstructed intensity map at distance $d = d_2 + Z_T/3$. The absence of multi-images formation at different Talbot planes is due to the high value of the duty cycle α of our pinhole array. Indeed, according to [24], the number of multiple images is smaller than $1/\alpha$. In our case the duty cycle value is about 0.6, and therefore multiple images cannot be formed in Talbot planes. This is also the reason why we have chosen these parameters for the grating. In fact, in case of a duty cycle larger then 0.5 the situation is less favorable, causing more overlapping among the images. On the contrary, in case of a lower duty cycle the images are much separated. So, being in the former case, we can demonstrate our technique in a less-favorable situation. The only in-focus image is then obtained for $d = d_1 + d_2$, which is on the target plane [see Fig. 2(b)]. It means that, in our case, the LN-ASF acts as a

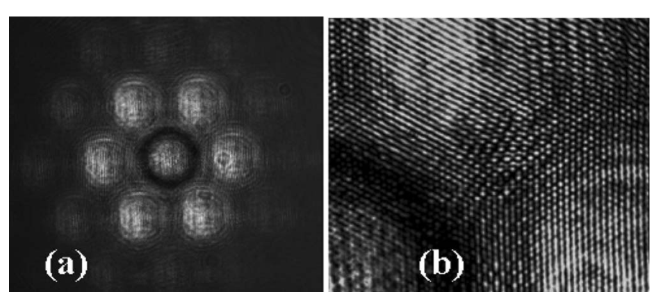

Fig. 3. (a) Typical acquired hologram with the different diffraction orders well visible. (b) Magnified view showing the overlapping among interference fringes.

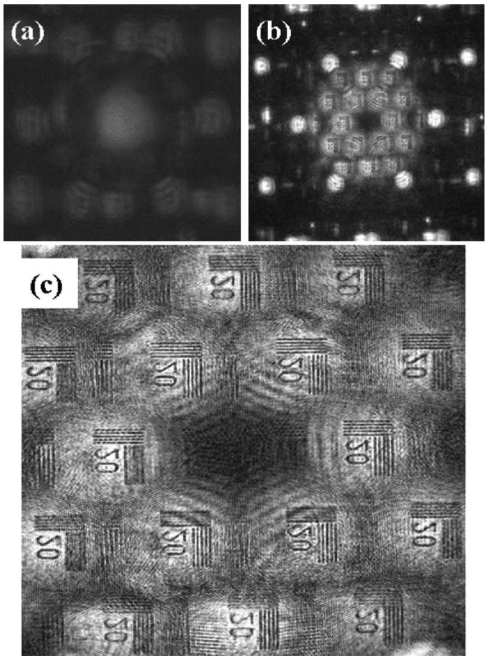

Fig. 4. (a) Reconstructed intensity map at a distance $Z_T/3$ from the LN-ASF. (b) Reconstructed in-focus virtual images and out of focus real images for each diffracted order, for $d=d_1+d_2$ (on the target plane). (c) Magnified view of the in-focus multi-images [central part of (b)].

microlens array with infinite focal length. Figure 4(b) shows both the reconstructed in-focus virtual images and the twin defocused real images for each diffracted order for $d=d_1+d_2$, while Fig. 4(c) displays a close-up of the in-focus multi-images.

In this work an alternative approach to get multi-images formation is proposed, making use of an hexagonal lithium niobate diffraction grating in combination with digital holographic technique. The advantage of this approach is twofold. First, it does not require optical elements, such as lenslet arrays, to be used, thus avoiding all the problems related with their fabrication. Second, it permits to overcome the constrains imposed by the parameters of the array (such as duty cycle, etc.) used in TAILs approaches. In fact, our diffraction grating is not used for the generation of in-focus multi-images in Talbot planes, but it is used only to separate the different diffraction orders of the object beam passing through it. These orders are then backpropagated and reconstructed by means of DH on the plane of the target, as if the grating were not present, obtaining this time in-focus multi-images of the original object. Moreover, the recorded digital hologram could be also processed by an SLM or digital micromirror device, thus obtaining optically reconstructed multi-images available for any further process (such as flexible lithography).

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