Phase-shifting Gabor holography

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We present a modified Gabor-like setup able to recover the complex amplitude distribution of the object wavefront from a set of inline recorded holograms. The proposed configuration is characterized by the insertion of a condenser lens and a spatial light modulator (SLM) into the classical Gabor configuration. The phase shift is introduced by the SLM that modulates the central spot (dc term) in an intermediate plane, without an additional reference beam. Experimental results validate the proposed method and produce superior results to the Gabor method. © 2009 Optical Society of America

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Six decades ago, Gabor proposed a new principle to achieve imaging in microscopy working without lenses [1]. This new kind of inline microscopy without lenses (or lensless microscopy) was aimed at overcoming the limitations due to the use of lenses in electron microscopy. The basic Gabor setup includes an inline configuration in which the nondiffracted light plays the role of reference beam that interferes with the diffracted components generated by the sample. Thus one can distinguish between two different regimes, depending on the object density. For samples blocking only a small part of the illumination light (low object density), the process is dominated by holography, and Gabor's concept could be applied. However, for high-density samples, the amount of light blocked by the object is significant, and diffraction dominates the process. In the former case, holographic recording means object reconstruction by classical holographic tools; in the latter case, diffraction prevents an accurate recovery of the object's complex wavefront.

One way to overcome this dilemma is by reinserting a reference beam at the recording plane. In this case, the reconstruction process will no longer be affected by the object's density owing to its holographic nature. The basic idea is to place the object information in one interferometric beam and the reference beam in a different one and bring them together to produce an interference pattern. Leith and Upatnieks [2–4] reported on different schemes based on an offline holographic architecture and thus avoided the distortion caused by overlapping, in the observation direction, of the three holographic terms incoming from the inline scheme.

Recent developments in solid-state image sensors and digital computers have enabled Gabor's original idea to be implemented by digital inline holographic microscopy, a powerful method for 3D imaging with micrometer resolution and the capability of tracking moving objects [5–8]. Moreover, digital sensors have produced a new way to evaluate the object complex amplitude distribution, considering an inline configuration. Thus, phase-shifting digital holography [9,10] removes the distortion incoming from twin images while optimizing the space-bandwidth product of the detector owing to the absence of carrier fringes in the recorded hologram in the offline configuration. Recently, Garcia-Sucerquia *et al.* reported on a new method to digitally process the inline holograms in a classical Gabor setup [11]. They showed that geometrical separation of twin image, high NA, and simple processing can greatly reduce the undesired terms, providing a relatively clean reconstruction. In any case, the reconstructed images will undergo higher or lower distortion, depending on both the density and the profile depth of the sample volume under study [12,13].

In this Letter, we present a new (to our knowledge) approach aimed at recovering the complex amplitude of the wavefront incoming from the sample in digital inline holography by using phase shifting without an additional reference arm. This approach is based on a Gabor-like setup but having two additional elements. The first one is a condenser lens added between the input sample and the CCD to provide focusing of the illumination at an intermediate (Fourier) plane. The second one is a spatial light modulator (SLM) placed in the Fourier plane. Thus, a phase-shifting algorithm can be performed by modulating the SLM pixels corresponding with the dc term of the object's spectrum.

Although other authors have also implemented common-path interferometric configurations where the dc term becomes modulated [14,15], those methods were used mainly to demonstrate wavefront sensing in imaging systems. Now, the proposed approach is applied to the field of digital microscopy, where two main advantages are derived from the use of the phase-shifting method. On one hand, it implies sample imaging with refocusing capability, where both zero-order terms and twin images are removed. This fact contributes to a better signal-to-noise ratio in the reconstructed images. In addition, owing to phase-distribution recovery, there is no need to perform coordinate transformation for high NAs and magnifications, because the complex amplitude distribution can be propagated exactly. Moreover, since magnification in an inline hologram is related to the distance between the illumination pinhole and the sample, the smaller the distance, the higher the magnification. As high magnifications are pursued in microscopy, the separation between twin and real images of the reconstructed hologram becomes small, because both of them are also related to the distance from the source to the sample. The proximity of the twin image will severely affect the quality of the reconstructed image. In our method, we avoid the twin image, and the reconstruction will not be distorted by it.

As depicted in Fig. 1, the experimental setup can be implemented in both transmissive and reflective configurations. In essence, a laser beam is focused by a collimation lens, and an SLM is placed at the focusing plane. Since the object stands after the lens and before the focusing plane, the object's spectrum (Fourier transformation of the object's complex amplitude distribution) will be generated over the SLM plane. Finally, a digital sensor (such as a CCD camera) captures the Fresnel pattern that is propagated a short distance from the SLM. A beam splitter is needed to allow recording for the inline holograms in the reflective case.

Since the central part of the object's spectrum is responsible for the dc term of the image, that is, for the nondiffracted light in the Gabor concept, it is possible to phase shift the recorded inline hologram in time by applying the phase modulation provided by the SLM to the pixel that spatially coincides with the dc term. Thus conventional phase-shifting algorithms can be applied by previously calibrating the SLM in order to know the phase step introduced by the SLM.

In this experimental proof of principle we have selected the reflective configuration. A laser beam (532 nm wavelength) is focused by a doublet lens (80 mm focal length) onto a reflective SLM (Holoeye HEO 1080 P, 1920 pixels × 1080 pixels resolution, 8 μm pixel pitch). The SLM is connected to a computer where the modulation is controlled by changing the gray level of the central pixel of the image that is transferred to the SLM. Finally, a beam splitter (20 mm × 20 mm) is used to reflect the light onto a CCD camera (Basler A312f, 582 pixels × 782 pixels, 8.3 μm pixel size, 12 bits/pixel). After calibration, the SLM provides 64 phase levels covering the required full 2π range. An accurate phase reconstruction is expected, as the pixel size of the SLM is smaller than the central lobe of the spectrum, given by the object extent and its distance to the CCD [16]. The method can be applied, provided that there is a dc term in its spectrum, without the need for weak diffraction assumption, as required for conventional Gabor holograms. Note that the reconstructed image excludes the part of the dc term that is used for phase modulation. This missing component can be neglected if the size of the modulated pixel is small, as compared with the dc lobe size, or can be simply added digitally.

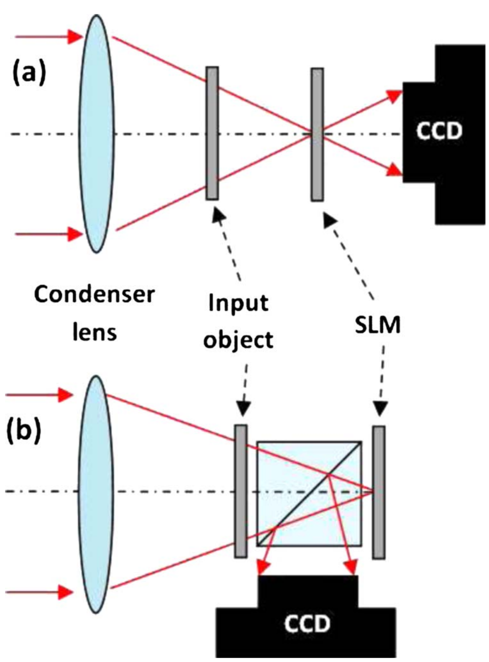

Fig. 1. (Color online) Sketch of the phase-shifting Gabor holographic setup: (a) transmissive and (b) reflective configurations.

Thus an inline hologram is recorded by the CCD and stored in the computer's memory for each of the 64 phases originating at the SLM. Figure 2 images one of the inline holograms while the full sequence (repeated three times) can be seen in Media 1.

Once the entire process is performed, the set of 64 images is processed using a conventional phase-shifting algorithm that takes into account the entire set of images [17]. Finally, the resulting distribution is digitally propagated into the object plane using the convolution method applied to the diffraction Rayleigh–Sommerfeld integral [17]. In this way, the diffraction integral can be numerically computed exactly by using three Fourier transformations through the convolution theorem, that is, $RS(x,y;d) = FT^{-1}\{FT\{U(x,y)\,R(x,y)\}\,(FT\{h(x,y;d)\}\}$, with $RS(x,y)$ as the propagated wave field, $U(x,y)$ as the processed hologram resulting from the phase-shifting algorithm, $R(x,y)$ as the reference wave, $h(x,y)$ as the impulse response, (x,y) as the spatial coordinates, FT as the numerical Fourier transform operation realized with the fast Fourier transform algorithm, and d as the propagation distance. Since we

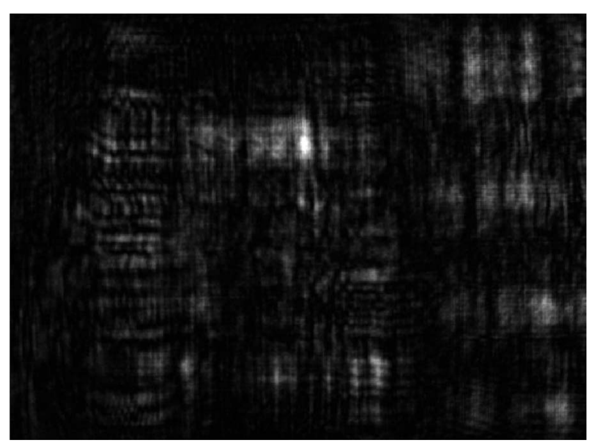

Fig. 2. Image of one of the 64 inline holograms recorded during the process (see Media 1).

directly define the Fourier transformation of the impulse response as $H(u,v;d)=FT\{h(x,y;d)\}$, with the spatial-frequency coordinates (u,v), the calculation of the propagated wave field to an arbitrary distance d is simplified to $RS(x,y;d)=FT^{-1}\{\hat{U}(u,v)H(u,v;d)\}$, where $\hat{U}(u,v)$ is the Fourier transformation of $U(x,y)$.

Figure 3 shows experimental results achieved using the proposed proof-of-principle method [case (a)] in comparison with one obtained when the same digital propagation is applied to one of the recorded holograms (Gabor's concept). One can see that the reconstruction using the classical Gabor inline holography setup does not produce useful imaging, because the object is highly nontransmissive; that is, it is a high-density object, and Gabor's concept cannot be applied. Notice that, because the CCD sensor is rectangular, Fig. 3(a) shows a different resolution limit in the horizontal and vertical directions.

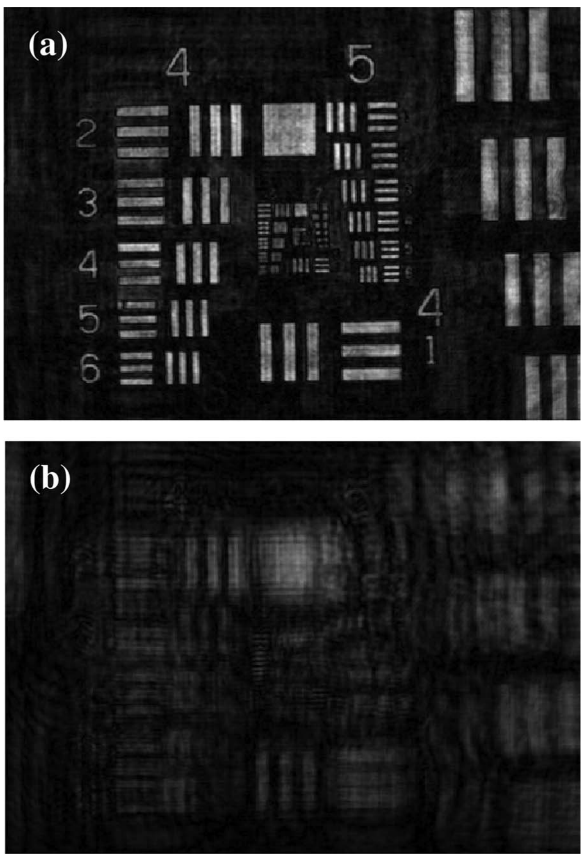

Fig. 3. Experimental results validating the proposed proof-of-principle approach: (a) the reconstructed image from the phase-shifting Gabor holographic method and (b) the reconstructed image using the classical Gabor method.

We have experimentally demonstrated the capabilities of a modified Gabor-like setup in order to recover the wavefront complex amplitude incoming from an object illuminated with laser light. The proposed proof of principle is based on the phase shift produced in the nondiffracted light (dc term) of the object's wavefront by using a single pixel of an SLM. The entire procedure implies the recovery of both phase and amplitude distributions and allows the digital backpropagation into the object's plane using numerically computed algorithms. The proposed method has unique advantages over the inline configuration (simplicity, robustness, and optimization of the space-bandwidth product adaption of the CCD) and from the phase-shifting method (distortionless image due to the twin-image removal and applicability to strongly diffracting objects).

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