Lensless Fourier transform digital holography with optical fiber based on spatial light modulator

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We proposed a novel method of using homogeneous-type nematic liquid crystal spatial light modulator (SLM) to electronically control the modification of reference beam in lensless Fourier transform digital holography (LFDH). By using nematic liquid crystal SLM as a phase-shifting device, which provides the advantage of avoiding any mechanical adjustments, the four-step phase-shifting technology can be realized availably. Furthermore, a convenient experimental setup for recording object in LFDH is presented. Almost perfect spherical reference wave can be acquired by using optical fiber, and the algorithm of median filtering is successfully employed in image processing to improve the quality of the reconstruction image.

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1. Introduction

In recent years, LFDH has attracted significant interest due to its unique feature [1-3]. Comparing with conventional Fresnel holography [4], the greatest differences of LFDH [5-6] are that its reference light is almost perfect spherical light rather than parallel light and it records the spatial frequency spectrum of object light instead of the complex amplitude. So we proposed to use optical fiber of high number aperture regarded as the reference point light source. In off-axis LFDH, both the zero-order image and conjugate image always reduce the quality of reconstruction image [7]. However, phase-shifting technology [8-9] can suppress them in a large part. The original phase-shifting technology was import the amount of phase-shifting in reference beam or object beam through piezoelectric ceramic micro-shifter (PZT), which was first invented by Yamaguchi and Zhang [10]. Although phase-shifting technology can improve the quality of reconstruction image [11], the error in phase-shifting processing throughout exists and the process of phase-shifting takes much time. At present, liquid crystal SLMs have seen rapidly growing interest owing to the fact that they are electro-optical devices which can change the lateral distribution of their complex transmittance depending on either electrical or optical external signals [12-13]. So liquid crystal SLM is gradually replacing PZT as a phase-shifting device applied in LFDH due to its unique liquidity and spatial anisotropism [14-15]. Therefore, we proposed to use homogeneous-type nematic liquid crystal SLM as a phase-shifting device to electronically control the modification of reference beam in LFDH, which provides the advantage of avoiding any mechanical adjustments in order to adapt the reference wave to different object positions. Therefore a convenient approach that use homogeneous-type nematic liquid crystal SLM as a phase-shifting device to lectronically control the modification of reference beam, which can realize four-step phase-shifting technology, and use optical fiber of high number aperture as the point source of reference beam is described in this paper. As a result, the zero-order image can be wiped out completely and the conjugate image can be wiped out more through the process of four-step phase-shifting technology by homogeneous-type nematic liquid crystal SLM in LFDH. Furthermore, speckle noise can be suppressed by both homogeneous-type nematic liquid crystal SLM and the image processing with median filter. In this paper, simple arrangement with optical fiber and homogeneous-type nematic liquid crystal SLM is presented. The recording and reconstruction of hologram is more skillful and convenient with this simple and flexible setup.

2. Principle

The reconstruction algorithm of LFDH is based on the Fresnel reconstruction algorithm, which was first invented by Schnars [16]. As shown in Fig.1, in off-axis LFDH, reference point light source R and object Obj are coplanar and both in the object plane (x_0, y_0), but not on the axis of the system. The coordinate of reference point light source on the X-axis is $(r, 0)$, and CCD is in the hologram plane (x, y). Let d_0 be the recording distance between the object plane and the hologram plane.

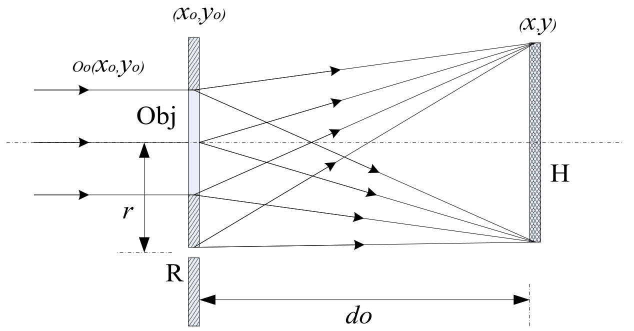

Fig. 1. Index path of lensless Fourier transform holography.

The reconstruction algorithm reads [17-18]:

$$b(x_I, y_I) = C\exp[-i\frac{\pi}{\lambda d_0}(x_0^2 + y_0^2)]FF\{h(x,y)r(x,y)\exp[-i\frac{\pi}{\lambda d_0}(x^2+y^2)]\} \quad (1)$$

where (x_I, y_I) indicates reconstruction image plane, C is a complex constant, λ is the wavelength, and FF indicates the two-dimensional Fourier transformation that has been modified by a factor of $1/\lambda d_O$.

In the recording configuration, the effect of the spherical phase factor associated with the Fresnel diffraction pattern of the object can be eliminated by using a spherical reference beam $r(x,y)$ with the same average curvature:

$$r(x,y) = C\exp[i\frac{\pi}{\lambda d_0}(x^2+y^2)] \quad . \quad (2)$$

A simple reconstruction algorithm can be described as follow:

$$b(x_I, y_I) = C\exp\left[-i\frac{\pi}{\lambda d_o}(x_o^2 + y_o^2)\right]FF[h(x,y)] \quad . (3)$$

Therefore, LFDH is reconstructed by one step of Fourier transform. In addition, the interference intensity distribution on the CCD plane can be described as follow:

$$\begin{aligned} I(x,y) &= |O(x,y) + R(x,y)|^2 \\ &= |O|^2 + |R|^2 + O*R + OR* \end{aligned} \quad , (4)$$

Where $O_{(x,y)}$ and $R_{(x,y)}$ denote the complex amplitudes of the object wave and reference wave on the CCD plane. The first two terms result in zero-order term in reconstruction process, the third term generates the conjugate image, and the forth term is the reconstructed object wave. In off-axis LFDH, the conjugate image, the reconstruction image and the zero-order term are spatially separated.

Homogeneous-type nematic liquid crystal SLM is the application of electrically controlled birefringence to achieve the phase modulation. The liquid crystal SLM adopted in the experiment of this paper is HOLOEYE LC 2002, as shown in Fig. 2, which is the production of Germany company. It is a twisted nematic phase liquid crystal, belong to transmission amplitude – phase hybrid modulation liquid crystal SLM. The size of the LCD of Holoeye LC 2002 is $26.6mm \times 20.0mm$, the maximum resolution is 832×624, the size of every pixel is $32 \times 32(\mu m)$. It can show a image in the level of 256 gray, its biggest frame frequency is $60Hz$.

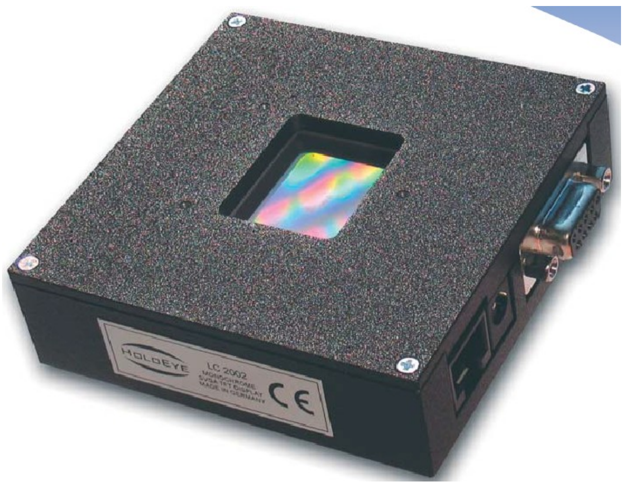

Fig. 2. HOLOEYE LC 2002.

Moreover, the amplitude function of homogeneous-type nematic liquid crystal SLM (Holoeye LC 2002) is:

$$t(x,y) = 0.5 + \frac{1}{4}\gamma\{\cos[2\pi f_0 x + \delta_1(x,y)] + \cos[2\pi f_0 y + \delta_2(x,y)]\} \quad (5)$$

Where δ_1 and δ_2 are the additional phase distributions imposed on the vertical and horizontal surface of SLM, respectively, and f_0 and γ are the spatial frequency and modulation depth of SLM, respectively. For the four-step phase-shifting with SLM, each mount of phase-shifting is

$0, \pi/2, \pi, 3\pi/2$ respectively. The complex amplitude distribution of corresponding reference light in the record surface is:

$$\begin{aligned} R_1 &= \exp(0)R(x,y) = R \\ R_2 &= \exp(j\pi/2)R(x,y) = jR \\ R_3 &= \exp(j\pi)R(x,y) = -R \\ R_4 &= \exp(j3\pi/2)R(x,y) = -jR \end{aligned} \tag{6}$$

And the intensity's distributions for each hologram have the following form:

$$\begin{aligned} I_1 &= |O|^2 + |R|^2 + O^*R + OR^* \\ I_2 &= |O|^2 + |R|^2 + jO^*R - jOR^* \\ I_3 &= |O|^2 + |R|^2 - O^*R - OR^* \\ I_4 &= |O|^2 + |R|^2 - jO^*R + jOR^* \end{aligned}, \tag{7}$$

1、j、-1、$-j$ multiplied by four pair of the above hologram, then add the left and right sides, respectively. And divid by four, the hologram of four-step phase shift can be expressed as:

$$\begin{aligned} I_{ps}(x,y) &= \frac{I_1 + jI_2 - I_3 - jI_4}{4} \\ &= O(x,y)R^*(x,y) \end{aligned}. \tag{8}$$

Equation (8) shows that both zero-order image and conjugate image can be wiped out with the four-step phase-shifting technology. As a result, the reconstruction of hologram is only the reconstructed object.

3. Experimental results

As shown in Fig. 3, a 532nm collimated laser beam passing through a beam splitter (BS), divides into two paths. One is reflected by the mirror (M), and then is expanded by an expender (EP1) to illuminate an object (a white dice, 12mm×12mm×12mm). The light scattered from the object is directly collected by a black-white CCD (the pixel size is 4.65μm×4.65μm, and the pixel amount is 960×1280). The other one, as a reference beam, the phase modification of which is electronically control by the homogeneous-type nematic liquid crystal SLM (Holoeye LC 2002, its pixel pith is 32μm×32μm, display resolution is 800×600), is expanded by an EP2, passing through a collimating lens (L1) and a converging lens (L2), and is focused into the ending face of optical fiber with high numerical aperture finally, which facing diameter is about a few micros. So the end of optical fiber can be represented as an almost-perfect point light source. The fiber employed in this work is sufficient long so the chromatic aberrations caused by lens can be avoided by adjusting the location of the end of fiber which is closed to the lens. The energy loss of the light emitted from the fiber is acceptable. The interference pattern is recorded by CCD. Fig. 3 shows the experimental setup of LFDH with homogeneous-type nematic liquid crystal SLM and optical fiber.

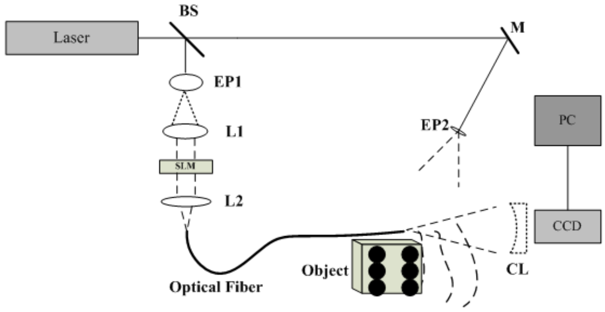

Fig. 3. Experimental setup for recording holograms.

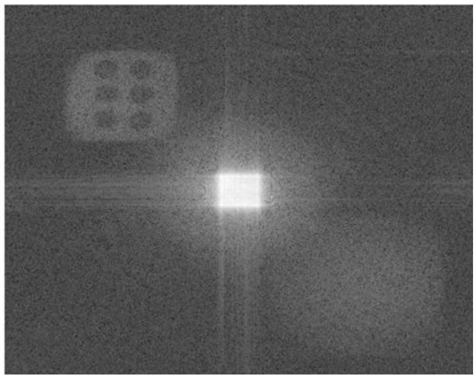

Fig. 4. Conventional Fresnel holography.

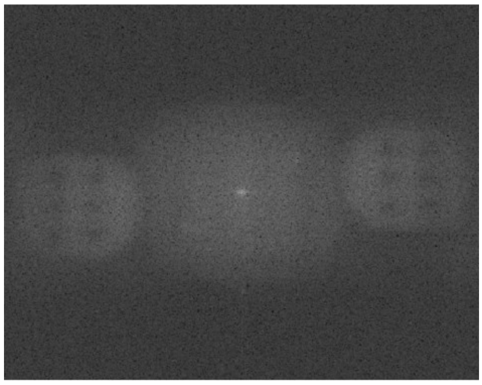

Fig. 5. LFDH with optical fiber and not processing phase-shifting with SLM.

Fig. 4 shows the conventional Fresnel holography without optical fiber. Fig. 3 shows the reconstructed image with optical fiber after the reconstruction algorithm of LFDH, which dose not process phase-shifting with nematic liquid crystal SLM. In off-axis LFDH with optical fiber, the beam emitted from optical fiber can be represented as spherical wave, that is better than a conventional practical point light which is focused by lens existing the spherical aberration. Moreover, the distance between object and the point source can be easily adjusted through the movement of the fiber. The range between the hologram recording and representation can be expanded through the concave lens (CL). Combined with the optical fiber in LFDH, the location of the object can be free, and the experimental setup is more skillful and convenient.

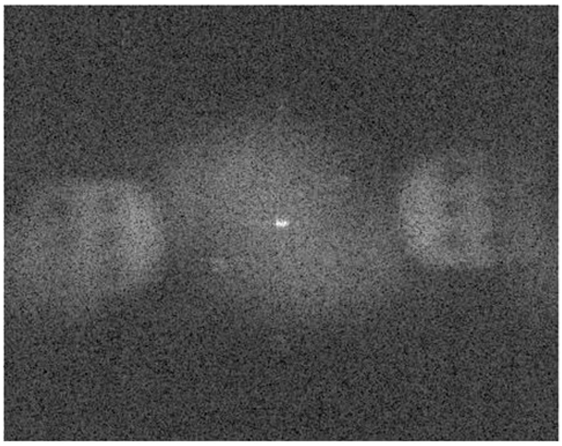

Fig. 4. Phase-shifting with polarizer.

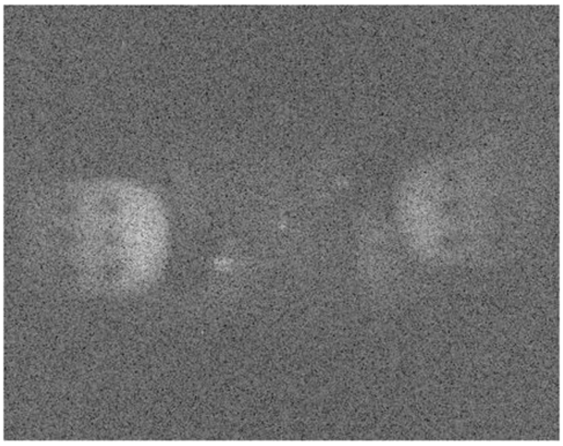

Fig. 5. Phase-shifting with SLM.

In the experiment of four-step phase-shifting with polarizer, the polarizer should be manually rotated four times, which produces major experimental noise. As a result, zero-order term and conjugate image can't be completely wiped out as shown in Fig.4. However, the veracity of phase modulation can be greatly improved with homogeneous-type nematic liquid crystal SLM as a phase-shifting device to lectronically control the modification of reference beam in this experiment, which can make the zero-order image being wiped out completely and eliminate the conjugate image more, the gained holograph is more brightness, as shown in Fig. 5. Compared with Fig. 4 and Fig. 5, the superiority of homogeneous-type nematic liquid crystal SLM can be confirmed. However, due to the influence of experimental environment and the limit of the reconstruction algorithm, the conjugate image couldn't be wipe out completely.

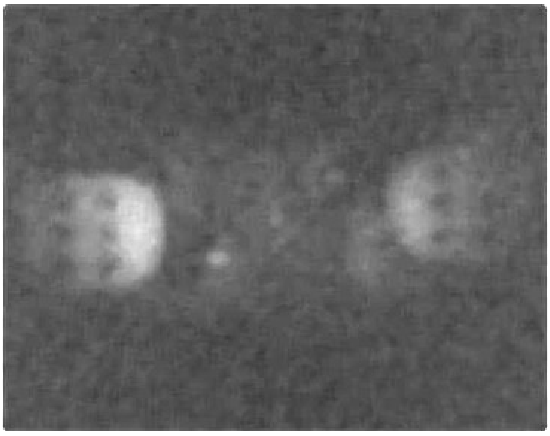

Fig. 6. The reconstruction after median filtering.

In this paper, median filtering is used to reduce the speckle noise after the operation of homomorphic transformation. The reconstruction image of Fig.5 after filtering process is displayed in Fig.6, which shows that the speckle noise decreases in a large extent, and more details of object can be reconstructed.

4. Conclusions

In order to acquire an accurate digital holographic image, homogeneous-type nematic liquid crystal SLM regarded as the phase-shifting device is applied in LFDH, it electronically controls the modification of reference beam and realizes four-step phase-shifting technology which can vastly reduce the noise of experimental environment and improve the accuracy of recording and reconstruction. In addition, optical fiber is used to emit a spherical reference beam of high number aperture. And speckle noise in reconstruction process can be decreased with median filtering. As a result, the quality of the reconstruction image can be greatly improved.

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