Analysis about System Parameters of Self-interference Incoherent Digital Holographic Recording System Utilizing Geometric Phase

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ABSTRACT

Self-interference incoherent digital holography utilizing the geometric phase lens has recently been developed with a super-simple design and the compactness of system structure. In this study, some of the acquisition performance related to the system parameters are analyzed to enhance the hologram acquisition quality.

1 INTRODUCTION

The self-interference incoherent digital holography (SIDH) is a famous method of recording the holograms under the incoherent light sources, such as the general lamps, fluorescent light, or the sunlight [1-3]. The key component in this system is the wavefront modulating device that imposes a difference in the incoming spherical wavefront curvature which is separated either by spatially or by its polarization states. Several systems are introduced with the different types of wavefront modulating devices, such as the conventional interferometric structure, calcite lens, liquid crystal graded index lens, and the phase-only SLM. Series of works of SIDH with the geometric phase (GP) lens is reported [4-6]. In the recent system, the system structure is dramatically simplified, which only consists of the lens, polarizer, GP lens, and the polarized image sensor. The illustration of the recent SIDH system with the GP lens is presented in Fig. 1.

The GP lens has a special optical characteristic that it can serve as a convex lens to the incoming right-handed circularly polarized (CP) wave while converting the handedness of the polarized states into the orthogonal one, and vice versa for the left-handed CP wave [7-9]. Due to this property, the spherical wave interference pattern of both converging and diverging spherical wavefronts is captured behind the GP lens. Under this geometry, the primary system parameters to acquire a robust quality of the hologram are the curvatures of two overlapping spherical wavefronts and the distance between the GP lens and the image sensor. In this study, the performance of hologram acquisition in SIDH system with the GP lens is demonstrated according to the system design.

2 Principle and optical path length analysis

The SIDH system with GP lens consists of the input objective lens, linear polarizer, GP lens, and the polarized image sensor. The incoming incoherent spherical wavefront is collected and collimated by the objective lens, and the polarizer defines its initial polarization state. After the GP lens, the linearly polarized wavefront is divided into two converging and diverging wavefronts. On the image sensor, the polarization states of both beams are redefined by the micro-polarizer array that is attached in front of the CMOS or CCD pixel, then the intensity of two wave interference is recorded by the pixel. The requirement of the polarized image sensor is for the sake of parallel phase-shifting that the single exposure of the sensor eliminates the bias and twin image information in real-time [10]. Therefore, when it comes to the temporal phase-shifting process, this component can be replaced into the general image sensor with the linear polarizer that is mounted on the rotary motor. After the four phase-shifted interferograms are obtained, the widely known recombination method is applied to extract the single complex hologram, by following the Eq. 1.

$$Hologram[p,q] = (I_0[p,q] - I_{180}[p,q]) - j(I_{90}[p,q] - I_{270}[p,q]), \quad (1)$$

where the [p, q] are the pixel indices, and $\mathrm{I}_{0,90,180,270}$ are the four phase-shifted intensity values at the same pixel location, respectively [11]. Finally, the object space is reconstructed from the recombined complex hologram via the propagation methods either by optically or numerically.

The two-wave interference is possible when the difference between the two ray traveling path distances is smaller than the coherence length ($\mathrm{l_c}$) of the utilized light source. The coherence length of the light source is calculated as $\lambda^2/\Delta\lambda$, where the numerator is the central wavelength of the source, and the denominator is the spectral bandwidth. In the incoherent holography, the coherence length of the input light is normally less than 15 μm, so that the requirement of the interference is hard to be fulfilled. The area of interference is dominantly limited in the SIDH system with GP lens due to this requirement. And the limited interference area leads to the poor quality of the reconstructed image. Therefore, it is important to enlarge the area of interference in this hologram acquisition system.

The optical path length difference (ΔOPL) between the interfering marginal rays is the maximum value, and it is calculated as Eq. 2 by following the labels illustrated in Fig. 1.

$$\Delta\mathrm{OPL} = \left\| \left[\sqrt{f_o^2 + \left(\frac{f_{gp} r_s}{f_{gp} - z_h}\right)^2} + z_h \sqrt{1 + \left(\frac{r_s}{f_{gp} - z_h}\right)^2} \right] - \left[\sqrt{f_o^2 + \left(\frac{f_{gp} r_s}{f_{gp} + z_h}\right)^2} + z_h \sqrt{1 + \left(\frac{r_s}{f_{gp} + z_h}\right)^2} \right] \right\| \qquad (2)$$

Where f_o is the focal length of the objective lens, f_{gp} is the focal length of the GP lens, r_s is the radius of marginal ray from the optical axis, and z_h is the GP lens to image sensor distance.

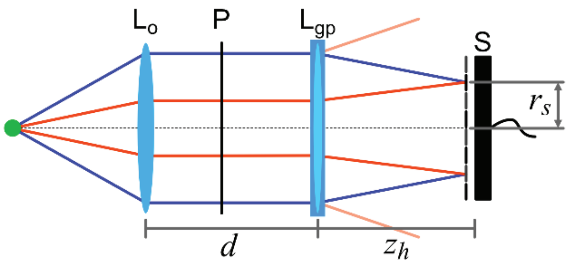


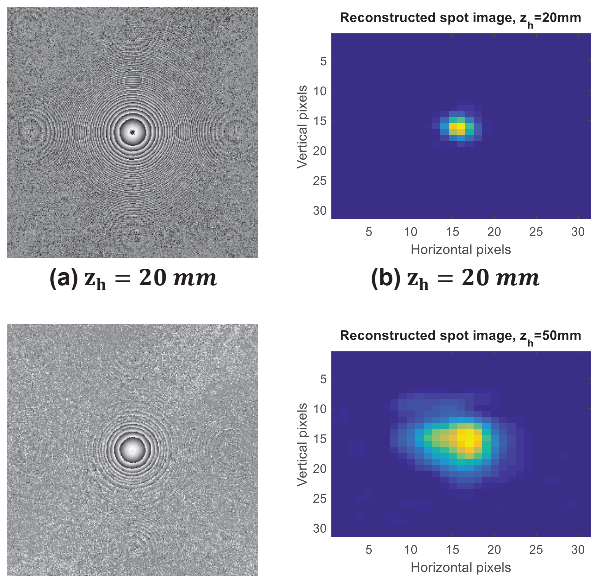
Fig. 1 Schematic illustration of the self-interference digital holographic recording system using the GP lens. L_o: objective lens, P: polarizer, L_{gp}: GP lens, S: image sensor (polarized).

Hence, the intensity of the interfering rays is captured only when the condition of $\Delta\mathrm{OPL} < l_c$ is fulfilled. This requirement of interference in the proposed incoherent holography system is dominantly determined by the utilization of the various focal length of the GP lens and the manipulation of the distance between the GP lens and sensor distance.

3 Demonstration of hologram acquisition quality related to system parameter

Figure 2 is the recorded holograms with phase-angle representation of the two different system structures, and the corresponding reconstructed images with best-of-focus plane. The sub-caption for each sub figure represents the distance z_h of each system, that is the distance between the GP lens and the image sensor plane, as illustrated in Fig. 1. The utilized target is the pinhole with 100 μm diameter. The illumination source of the target is the light emitting diode where the central wavelength is of 550 nm and the spectral bandwidth of 31 nm. The focal length of the objective lens is 100 mm. The distance d is about 22 mm. The focal length f_{gp} is about 271 mm for the incoming wavelength of 550 nm. The distance z_h is 20 mm for the results of Fig. 2(a,b) and 50 mm for Fig. 2(c,d), respectively.

The expected hologram area, or the recorded area of the fringe patterns over the random phase noise, is reduced in the system with z_h = 50 mm according to the requirement that the optical path length difference between the two interfering rays should be smaller than the coherence length of the light source. This feature is easily noticed from the aliased patterns of the quadratic phase profile in Fig. 2(a), which is due to the fine fringe patterns that cannot be presented by the pixelated structure of the figure. Meanwhile, the aliased pattern is not observed in Fig. 2(c) since there is no such fine fringe patterns. The reconstructed point spot width is broadened in the image reconstructed from the Fig. 2(c). This result suggests one requirement in the proposed system that the better result is obtained with the shorter z_h value.



(a) $z_h = 20\ mm$ (b) $z_h = 20\ mm$

(c) $z_h = 50\ mm$ (d) $z_h = 50\ mm$

Fig. 2 Hologram recording result with different system parameters, (a, c) hologram of a point source (phase-angle) (b, d) reconstructed spot image from (a) and (c), respectively.

4 CONCLUSIONS

The hologram acquisition performance of the self-interference incoherent digital holography with the geometric phase lens is briefly analyzed in this study. As discussed, the quality of the hologram and its retrieved image is higher as the system structure is shortened, especially the distance between the GP lens and the image sensor. Therefore, this system can be easily implemented in the various mobile devices with the further optimizations.

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