Study of self-interference incoherent digital holography for the application of retinal imaging

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ABSTRACT

Adaptive optics (AO) using digital holography (DH) is more effective in terms of complexity and cost than other AO techniques. However, use of coherent illumination is problematic in applying DHAO for retinal imaging because of speckle noise. Self-interference incoherent digital holography (SIDH) is a technique to record holographic information from the object illuminated by incoherent light. By adopting SIDH for the full-field imaging, the speckle noise problem can be avoided with incoherent illumination. However, the guide-star hologram for AO requires the guide-star to be smaller than retinal cell size to achieve sufficient resolution. Hence, the proposed SIDH AO system is configured with a hybrid illumination system which uses incoherent illumination for recording of full-field hologram while laser is used for guide-star hologram. Preliminary experiment using an array of micro-spheres for the object shows that the full-field hologram and guide-star hologram can be recorded by proposed optical configuration.

Keywords: incoherent digital holography, adaptive optics, retinal imaging, aberration compensation

1. INTRODUCTION

Adaptive optics (AO) technique has been developed in the astronomical imaging to compensate the distortion of acquired image which is induced by the atmospheric turbulence [1, 2]. In conventional AO technique, the information about the turbulence is usually recorded by using a Shack-Hartmann or pyramid wavefront sensor. The recorded information is used for compensating the distortion by a deformable mirror or spatial light modulator (SLM) in real time. For the application where the digital holographic imaging is applicable, AO can be implemented more easily [3]. The information of the aberration is recorded as a guide-star hologram and the compensation can be done by simple calculation without any expensive device or huge computation. Moreover, because the guide-star hologram is recorded by using full resolution of CCD, the digital holographic AO (DHAO) is expected to extract more accurate information of aberration.

For ocular imaging, the entire optical system (but mostly cornea) of human eye induces aberration which deteriorates the quality of recorded image. To compensate such aberration, AO technique is necessary for many ophthalmic applications such as scanning laser ophthalmoscopy [4] and optical coherence tomography [5]. However, if we consider DHAO for the retinal imaging, the speckle noise induced by laser can severely affect to the image quality because the retinal cells are relatively small. Hence, incoherent illumination can resolve the speckle noise problem in applying DHAO for retinal imaging.

2. ADAPTIVE OPTICS USING SELF-INTERFERENCE INCOHERENT DIGITAL HOLOGRAPHY

Self-interference incoherent digital holography (SIDH) is one of techniques which can record the holographic information from the object illuminated by the incoherent light. Though the investigation about the possibility of incoherent holography was already conducted from the early history of the holography in the literature [6, 7], it has begun to obtain meaningful results in just recent few years with aid of the development of electronic devices and computer science. It is different from the low coherent illumination because it doesn't need any constraint or manipulation to the illumination source. SIDH can even be applied for recording of holographic information of the natural outdoor scene which is illuminated by the sunlight. Recently, our group has reported about the implementation of full-color holographic camera which can record the holographic information of natural outdoor scene [8]. SIDH can also be applied for the fluorescence microscopy which was not possible to record the image using conventional holographic technique [9]. Hence, AO using SIDH can be an ideal alternative to DHAO to avoid the speckle noise problem.

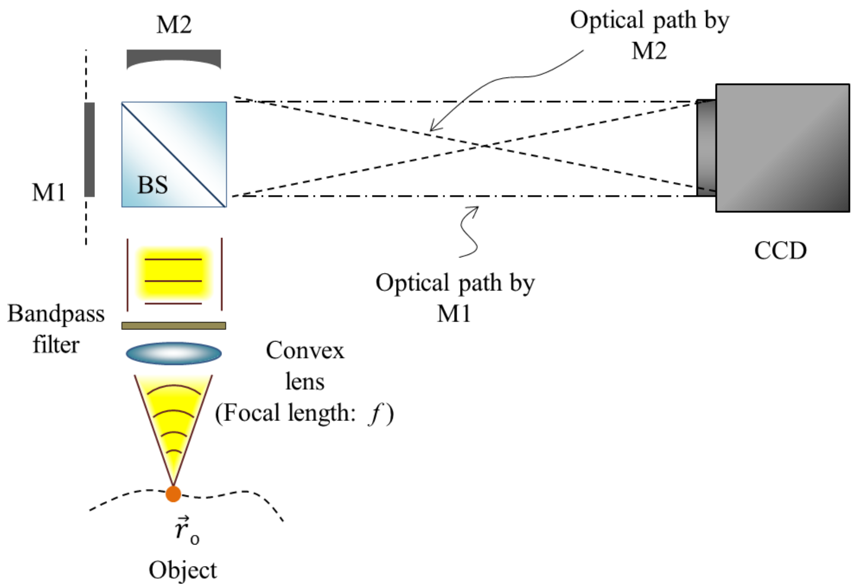


Figure 1. Brief optical configuration of SIDH. M1: plane mirror; M2: curved mirror.

Figure 1 shows a brief description of the optical configuration for SIDH. Considering light emanated from one specific point on the object surface, it becomes close to the plane wave when the object is located near the focal length of the input lens of system. After passing through the beam splitter, it is separated to two copies of beams and they are reflected by two mirrors – plane and concave mirrors. Reflection by those two mirrors imposes different curvatures to two copies of beams and results in the interference at the CCD plane. The best location for CCD to record the interferogram is a plane where two copies of beams exactly overlap. The interferogram obtained by the point source at the optic axis will have a form of:

$$u(\mathbf{r}, z_o) = A\left[1+\cos\varphi(\mathbf{r}; z_o)\right], \tag{1}$$

where φ is a quadratic function dependent on $\mathbf{r}$, coordinate on CCD plane. z_o is the distance between the object plane and the input lens of system. Considering all the contributions from the object plane, the entire interferogram will be:

$$U(\mathbf{r}; z_o) = I(z_o) \odot u(z_o). \tag{2}$$

To obtain the complex hologram from the recorded interferogram, three or four-steps of phase shifting technique is usually adopted. By moving one of the mirrors slightly, the phase-shift can be implemented and the response to point source will be:

$$u_\theta(\mathbf{r}; z_o) = A\left[1+\cos\left(\varphi(\mathbf{r}; z_o)+\theta\right)\right], \tag{3}$$

where θ is a phase-shift value. Because φ is a quadratic function, the complex hologram of each point source will become a quadratic phase function $Q(\mathbf{r}; z_o) = \exp[iC(z_o)|\mathbf{r}|^2]$ where $C(z_o)$ is a constant dependent on z_o. Hence, the entire complex hologram acquired by SIDH will be a convolution of object and quadratic function:

$$H(\mathbf{r}; z_o) = I(z_o) \odot Q(z_o). \tag{4}$$

Hence, by applying a simple Fresnel propagation to the complex hologram, the object image can be simply reconstructed. However, when an aberration exists among the optical path between object and CCD, this relationship is broken down and the object image cannot be obtained correctly if the aberration was not compensated in any way. For some applications such as astronomic or ophthalmic imaging, it had been revealed that the aberration compensation using guide-star can be useful. Recently, our group has reported that aberration compensation using guide-star also can be applied in SIDH [10]. The major difference in SIDH is that the compensation process can be done as a post-processing unlike usual real-time compensation using deformable mirror because the guide-star information is recorded as a complex hologram. When the focal length of the curved mirror is sufficiently large, the complex hologram obtained from the object under the condition where the aberration is present will be:

$$H_{\Psi}(\mathbf{r};z_o)=I(z_o)\odot G_{\Psi}(z_o),\tag{5}$$

where G_{Ψ} indicates the guide-star hologram under a certain circumstance. Hence, if we know the guide-star hologram, the object image can be estimated by:

$$\hat{I}(\mathbf{r_o};z_o)=H_{\Psi}(z_o)\otimes G_{\Psi}(z_o),\tag{6}$$

which compensates aberration using cross-correlation with guide-star hologram.

3. OPTICAL CONFIGURATION FOR RETINAL IMAGING

To apply AO using SIDH, the optical configuration of the imaging system should provide the illumination source which is capable of creating guide-star and full-field hologram. For the creation of the guide-star, the illumination should make a spot as small as possible on the sample surface because it determines the resolution of the compensated image. After compensation, the resolution of the reconstructed image cannot be smaller than the spot size of the guide-star. Hence, the ideal spot size of the guide-star should be smaller than the expected resolution of the reconstructed image (i.e. retinal cell size). Because we are considering the retina cells as a sample, the spot size of the guide-star hologram should be limited by few microns. For this purpose, it is better to use a laser as an illumination source instead of LED because it is easier to provide a nice plane wave with wide coverage and sufficient optical power. Moreover, the speckle noise is not the problem for the guide-star hologram. Hence, to take an advantage both from coherent and incoherent illumination, it is better to configure a hybrid illumination system which uses laser for the creation of the artificial guide-star and LED for the full-field imaging.

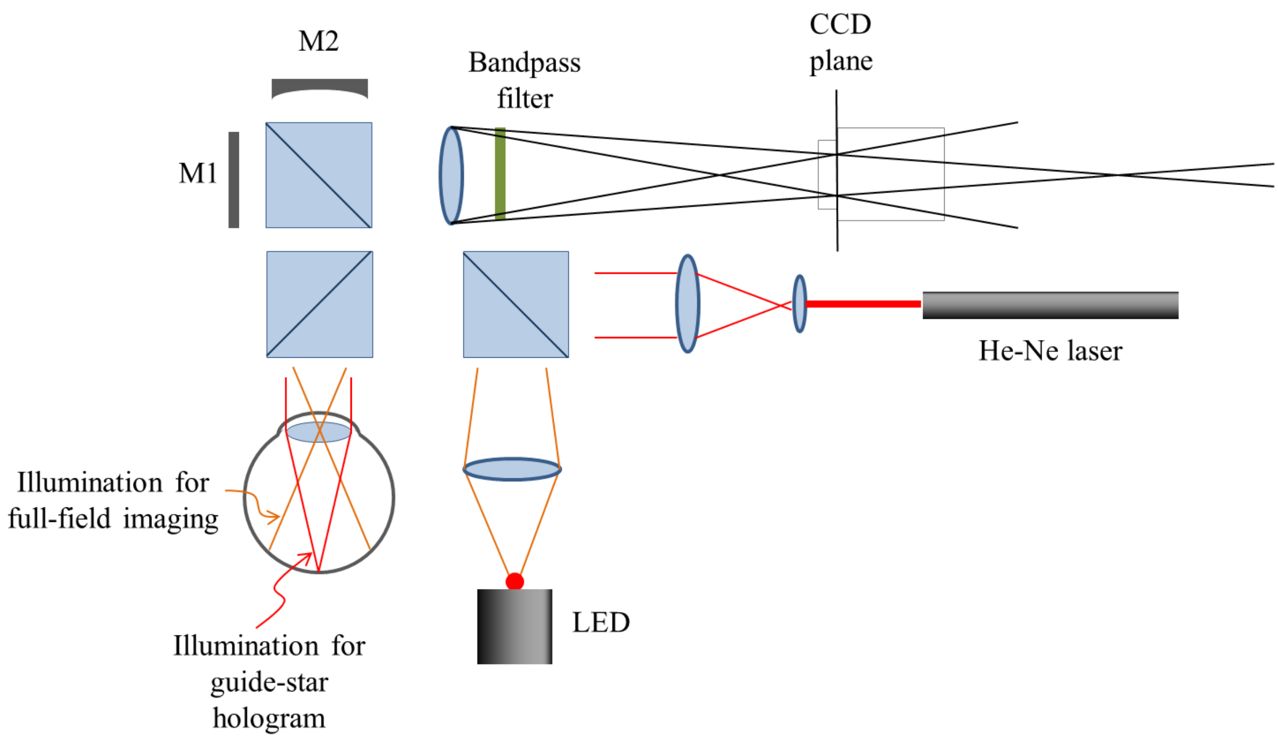


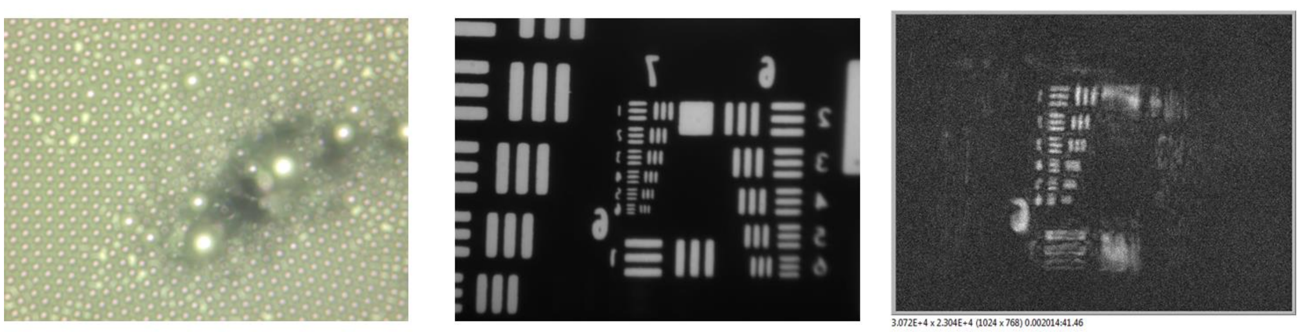
Figure 2. Optical configuration to apply SIDH AO for retinal imaging.

Figure 2 describes the conceptual diagram of the optical setup for performing SIDH AO which can be used for retinal imaging. For the full-field imaging, illumination from LED is configured to focus on the eye lens by location a certain lens in front of LED. Then LED illumination can cover the entire FOV on the retinal surface. For laser illumination, a beam expander is located in front of laser to cover the area of eye pupil. Then it is focused on the retinal surface to make an artificial guide-star. Appropriate shutters will be located in front of both LED and laser to select one of them according to its usage. After illumination, the scattering from retinal surface is recorded by SIDH system as holographic information. To provide the flexibility to the configuration, we locate an additional output lens in front of CCD. Using recorded guide-star and full-field holograms, the aberration can be compensated using Eq. (6).

One more thing to consider is a magnification. To see retinal cells using the system, magnification of the system should be high enough to resolve each cell. Technically, each cell will be barely resolvable if the resolution on the CCD plane becomes at least twice higher than the size of the each retinal cell. However, we empirically know that 10 ~ 20x magnification is required to clearly see the retinal cells using the CCD which has 4.65 μm pixel size.

4. EXPERIMENTAL RESULTS

We have performed a preliminary experiment to investigate the performance of SIDH system for the retinal imaging. Instead of real retina sample, we used an array of micro-spheres to mimic the cone mosaic of retina. The size of each micro-sphere was 6 μm and we prepared a closely packed monolayer of spheres. Figure 3(a) shows the photo of the prepared micro-spheres array under the commercial microscope with 20x magnification. For the experiment, we configured the system to have approximately 15x magnification and there was no severe aberration on the input lens. Figure 3(b) and (c) respectively show the direct image and the holographic reconstruction of resolution target to measure FOV of system (for direct imaging, the reflection from curved mirror was blocked). We can see that the system can clearly resolve the details smaller than 2 μm for the direct image while the resolution of holographic reconstruction from SIDH imaging is little worse as shown in Fig. 3(c). However, the resolution is still high enough to resolve each micro-sphere in the sample shown in Fig. 3(a).



Micro-spheres array　　Direct image　　Reconstruction

Figure 3. Image of micro spheres array was obtained by a commercial microscope with 20x magnification; Images of resolution target was obtained by SIDH system prepared for the experiment.

Figure 4 shows the experimental results of imaging micro-spheres array using the prepared SIDH system. Direct image clearly shows that the magnification is sufficiently high to resolve each sphere. From recorded inteferograms, we could obtain the complex hologram. The phase of complex hologram clearly shows collection of quadratic phase functions, but the size of each quadratic phase function occupies just small area of entire screen. Because this system does not have significant aberration, simple Fresnel propagation shows clear reconstruction of the object image. Though the resolution of the reconstructed image is sufficient, the current magnification seems to be barely acceptable for the actual retinal cells.

Figure 5 shows the recording of guide-star hologram using the same micro-spheres array illuminated by He-Ne laser. NA of the input lens is 0.25 and the illumination was expanded to fully cover the aperture. Hence the expected spot size on the surface of the sample is supposed to be around 3 μm which is smaller than one sphere size. A shape of the phase of retrieved complex hologram is close to quadratic phase function which is expected for the aberration-free condition. The problem here is that the phase information cannot cover sufficiently large area on CCD plane. To obtain the appropriate information about the aberration, the system parameters should be designed to enlarge the overlap of two copies of beams on the CCD plane.

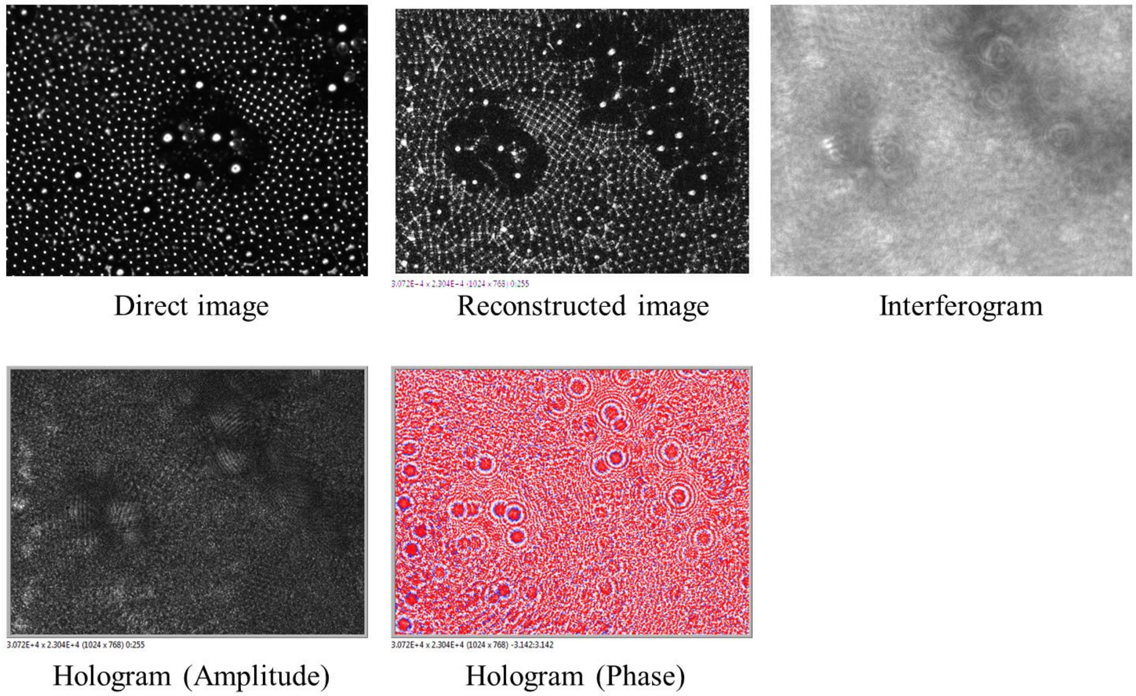


Figure 4. Experimental results of full-field imaging using SIDH. Sample is an array of micro-spheres (diameter: 6 μm)

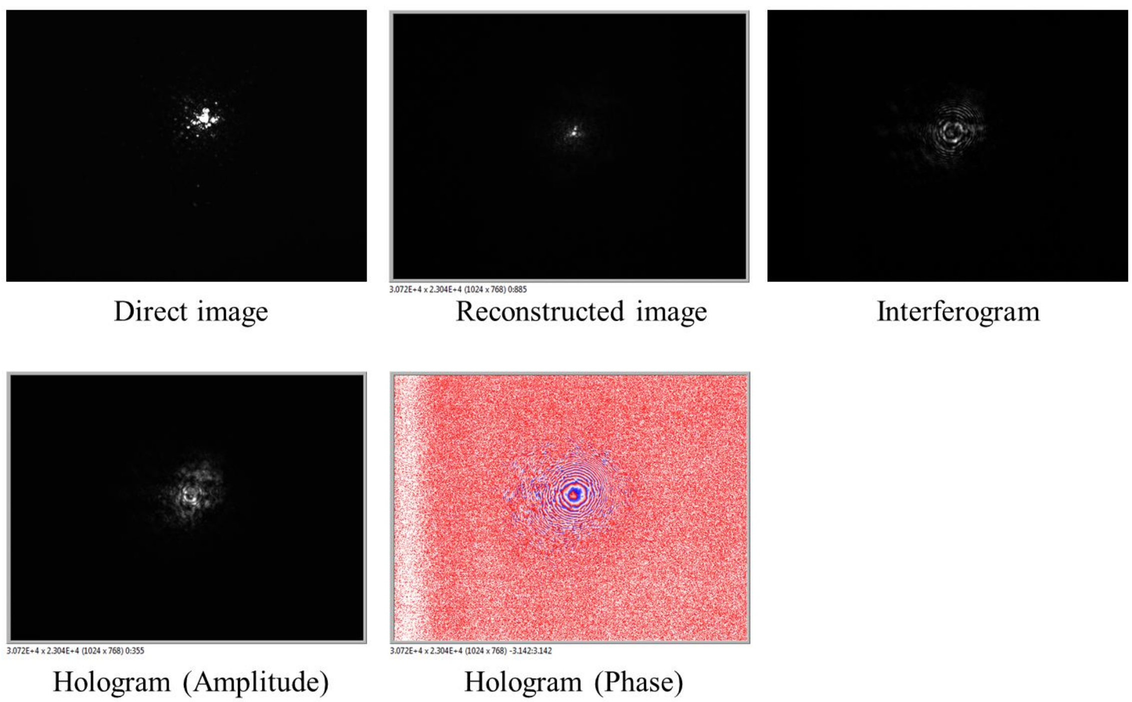


Figure 5. Experimental results of imaging guide-star using prepared SIDH system.

5. CONCLUSION

We proposed a scheme which can compensate the aberration of human eye by using SIDH AO. Because SIDH records the holographic information by incoherent illumination, it is expected to acquire clear retinal imaging without speckle noise. In recording a guide-star hologram, creation of nice and sufficiently small guide-star is a major concern. Hence, the proposed system adopts a hybrid illumination system to provide laser illumination for recording guide-star hologram. The experimental results using an array of micro-spheres as an alternative to real retina sample have shown the possibility of proposed method. However, the system parameters should be modified to enlarge the size of guide-star hologram to convey more information about the aberration.

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