Single-shot Fresnel incoherent digital holography based on geometric phase lens

Dong Lianga,b,c, Qiu Zhangb,c, Jing Wanga,c and Jun Liub,c

aSchool of Physics Science and Engineering, Tongji University, Shanghai, People’s Republic of China; bState Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai, People’s Republic of China; cCenter of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing, People’s Republic of China

ABSTRACT

Single-shot and incoherent imaging are two important properties of digital holography that can extend its application range. In this study, a simple, compact, in-line Fresnel incoherent digital holographic recording system is proposed that is capable of single-shot and three-dimensional imaging. A geometric phase lens is used as the common-path beam splitter based on its special wave separation property. Parallel phase-shifting holography is used to achieve single-shot operation with the use of a polarization imaging camera together with space-division multiplexing. The capabilities of the proposed technique are experimentally confirmed by imaging two standard test charts based on a compact setup.

ARTICLE HISTORY

Received 5 May 2019
Accepted 6 November 2019

KEYWORDS

Single-shot; incoherent digital holography; three-dimensional imaging; space-division multiplexing; Parallel phase-shifting method; geometric phase lens

Introduction

Digital holography is a powerful technique capable of recording three-dimensional (3D) information using an image sensor and retrieving the amplitude and phase of an object with a computer (1). It has been extensively used in numerous research fields, including 3D optical display (2), object recognition (3), and in quantitative phase imaging of biological samples (4). Among the existing digital holographic techniques, incoherent digital holography constitutes one of the important research fields because it can avoid speckle noise and spurious interference owing to the use of incoherent light sources. Furthermore, it extends the applications of traditional digital holography to imaging using incoherent light, with fluorescence microscopy and white light imaging being characteristic examples (5,6). Among the incoherent holographic methods – unlike multiple view projection holography (7), scanning holography (8), and other incoherent holographic methods – Fresnel incoherent correlation holography (FINCH) (9) is a non-scanning and motionless method used to generate holograms that has recently received increased attention. In FINCH, the spatial light modulator (SLM) splits the spherical wave that originates from each object point into two spherical waves with different curvatures. These waves are then recombined at an imaging plane to produce interference fringes. Therefore, separating waves with different curvatures is an important step in the FINCH system.

Accordingly, the emergence of high-performance SLM provides a flexible and convenient method to separate waves with different curvatures for this type of incoherent holography. Based on a co-axial holographic recording configuration, the phase-shifting interferometry method can be used to effectively eliminate undesired diffraction and twin images from an object wave. Thereafter, noiseless images are obtained based on the use of a numerical reconstruction algorithm with the use of a computer.

FINCH has achieved many remarkable results on the suppression of the direct current (DC) term and conjugate image (10,11), and has led to spatial resolution and image quality improvements (12,13) in the past decade. Recently, some incoherent digital holography systems based on SLM or other wave-splitting devices have been reported (14–17). To this date, the phase-only SLM is the most common device used as a wave separator for a FINCH system owing to its convenience in achieving tuneable phase patterns. However, the phase-only SLM increases the complexity and cost of these incoherent digital holography systems which ultimately limits their broad range of applications.

To simplify the setup, the geometric phase (GP) lens is introduced to the FINCH system to replace the above mentioned complex and expensive SLM or birefringent crystal lens (18–20). By using a polarized camera as the detector, single-shot FINCH that is capable of single-shot...
and three-dimensional imaging can be achieved with a simple, compact, and cost-effective optical setup.

**Principle and experimental setup**

The GP lens we used in the FINCH system employs photo-aligned liquid crystal layers to implement the spatially varying Pancharatnam–Berry phase (21), thus leading to the expected polarization depending on the focal properties. Owing to the special properties of a GP lens, left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP) light can be focussed with the respective use of positive or negative focal lengths. Regarding the linearly polarized light, the GP lens will also act as a positive and a negative lens at a 50:50 light intensity ratio. Moreover, the GP lens has high transmission efficiency in the 450–650 nm spectral range, and has a simple structure and a low cost. Single-lens imaging experiments conducted with the use of GP, plan-convex, Fresnel, and aspherised achromatic lenses, showed that the GP lens yielded high-image quality (22). It is worth noting that the two beams possessed different (opposite) curvatures are LHCP and RHCP light, respectively. Therefore, such a GP lens is a perfect wave separator for wave fronts with different curvatures in FINCH systems.

The basic principle of a FINCH system with a GP lens is shown in Figure 1. Based on the expressions of the FINCH system proposed by Rosen and Brooker (9), we describe the entire system by means of mathematical formulations, equations, and quantitative explanations. An ordinary convex lens is used to collect the incoherent light from the object point which is located at \( z_0 \) from the convex lens \( L \). The complex amplitude distribution before the lens can be described by Equation (1):

\[
U_1 = C(r_0, z_0) L \left( \frac{r_0}{z_0} \right) Q \left( \frac{1}{z_0} \right)
\]

where \( C(r_0, z_0) \) is the complex constant associated with the point-object source, \( r_0 = (x_0, y_0) \) are the point-object coordinates, \( L(r_0) = \exp[i2\pi\lambda^{-1}(x_0x + y_0y)] \) is the linear phase function, and \( Q(b) = \exp[i\pi b\lambda^{-1} (x^2 + y^2)] \) is the quadratic phase function. Herein, \( \lambda \) is the central wavelength of the point-object source. Given that the lens can change the spatial phase distribution of the light wave, the complex amplitude of the field after the convex lens is expressed by Equation (2):

\[
U_2 = U_1 \times Q \left( \frac{1}{-f_0} \right)
\]

Herein, \( Q(1/f_0) \) is the transmission function of the convex lens, and \( f_0 \) is the focal length of the lens. Assuming propagation in free space at a distance \( d \), the field distribution before the GP lens can be described as,

\[
U_3 = U_2 \ast Q \left( \frac{1}{d} \right)
\]

where \( \ast \) denotes a convolution operation. The field then propagates through the GP lens. The GP lens simultaneously divides the beam into a converging part with a focal length of \( +f_{GP} \) and a diverging part with a focal length of \( -f_{GP} \). It also introduces the phase shifts of \( \phi/2 \) and \( -\phi/2 \), respectively. Herein, \( \phi \) is the phase shifting value produced by the GP lens. Thus, the transmission function of the GP lens is expressed as \( [Q(1/(-f_{GP}))e^{i\phi/2} + Q(1/f_{GP})e^{-(i\phi/2)}]/2 \). After the GP lens, the field propagates through free space at a distance \( z \) to reach the image sensor. The complex amplitude distribution can be expressed as,

\[
U_4 = U_3 \times \left[ Q \left( \frac{1}{-f_{GP}} \right) e^{i\phi/2} + Q \left( \frac{1}{f_{GP}} \right) e^{-(i\phi/2)} \right] \ast Q \left( \frac{1}{z} \right)
\]

Accordingly, the intensity distribution of the object point recorded on the image sensor is \( I_h \).

\[
I_h = |U_4|^2 = C + C_1 \exp \left\{ \frac{i\pi}{\lambda z_{rec}} [(x - M_m x_0)^2 + \cdots] \right\}
\]

**Figure 1.** Schematic of the FINCH system (GP lens, geometric phase lens; CCD, charge-coupled device; L, convex lens; P, linear polarizer).
Herein, the complex reconstruction process, an image of the object can be obtained by utilizing the phase-shifting method (Equation (5)), the typical four-step phase-shifting technique. Accordingly, four-step phase-shifting holograms are mathematically generated based on the processes of de-mosaicing and interpolation of the recorded single-shot hologram. In the de-mosaicing procedure, the data on each pixel that correspond to different polarisations for each phase-shifted hologram are extracted separately, as shown in Figure 2(b). As a result, the other three vacant pixels of each phase-shifted hologram are interpolated using the extracted data of neighbouring pixels. Herein, we demonstrate the process of four-phase shift holograms using a linear interpolation scheme, which can be represented using the following expressions:

\[ I(m, n) = \begin{cases} 
    I(m, n), \\
    [I(m, n - 1) + I(m, n + 1)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n - 1) + I(m - 1, n + 1) + I(m + 1, n + 1)]/4, \\
    [I(m - 1, n) + I(m + 1, n)]/2, \\
\end{cases} \]

\[ I(m, n : 45^\circ) = \begin{cases} 
    [I(m - 1, n) + I(m + 1, n)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n - 1)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n + 1)]/4, \\
    [I(m - 1, n) + I(m + 1, n)]/2, \\
\end{cases} \]

\[ I(m, n : 90^\circ) = \begin{cases} 
    [I(m - 1, n) + I(m + 1, n)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n - 1)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n + 1)]/4, \\
    [I(m - 1, n) + I(m + 1, n)]/2, \\
\end{cases} \]

\[ I(m, n : 135^\circ) = \begin{cases} 
    [I(m - 1, n) + I(m + 1, n)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n - 1)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n + 1)]/4, \\
    [I(m, n - 1) + I(m, n + 1)]/2, \\
\end{cases} \]

where \( m \) and \( n \) are the coordinates of the target pixel. In effect, the value of the central vacant pixel, which is some fast and instantaneous imaging processes. Furthermore, the hologram collected in every step of the phase-shifting method may be disturbed by the environment which will affect the quality of the reconstructed image. Parallel phase-shifting digital holography uses a polarization imaging camera with a micro-polarizer array, and can capture a single-shot hologram which contains the information of multiple phase-shifted interferograms (24,25). Figure 2 explains the principle of the parallel phase-shifting technique. Accordingly, four-step phase-shifting holograms are mathematically generated based on the processes of de-mosaicing and interpolation of the recorded single-shot hologram. In the de-mosaicing procedure, the data on each pixel that correspond to different polarisations for each phase-shifted hologram are extracted separately, as shown in Figure 2(b). As a result, the other three vacant pixels of each phase-shifted hologram are interpolated using the extracted data of neighbouring pixels. Herein, we demonstrate the process of four-phase shift holograms using a linear interpolation scheme, which can be represented using the following expressions:

\[ I(m, n) = \begin{cases} 
    I(m, n), \\
    [I(m, n - 1) + I(m, n + 1)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n - 1) + I(m - 1, n + 1) + I(m + 1, n + 1)]/4, \\
    [I(m - 1, n) + I(m + 1, n)]/2, \\
\end{cases} \]

\[ I(m, n : 45^\circ) = \begin{cases} 
    [I(m - 1, n) + I(m + 1, n)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n - 1)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n + 1)]/4, \\
    [I(m - 1, n) + I(m + 1, n)]/2, \\
\end{cases} \]

\[ I(m, n : 90^\circ) = \begin{cases} 
    [I(m - 1, n) + I(m + 1, n)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n - 1)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n + 1)]/4, \\
    [I(m - 1, n) + I(m + 1, n)]/2, \\
\end{cases} \]

\[ I(m, n : 135^\circ) = \begin{cases} 
    [I(m - 1, n) + I(m + 1, n)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n - 1)]/2, \\
    [I(m - 1, n - 1) + I(m + 1, n + 1)]/4, \\
    [I(m, n - 1) + I(m, n + 1)]/2, \\
\end{cases} \]
surrounded by four filled pixels, is the average of these four neighbouring pixels. The value of the vacant pixel in between the two filled pixels is also the average of these two neighbouring pixels, as shown in Figure 2(b,c). Thus, multiple phase-shifted holograms required for single-shot phase shifting interferometry can be mathematically generated.

Based on the GP lens and the polarization imaging camera mentioned above, a novel single-shot FINCH is proposed, as shown in Figure 3. An ordinary convex lens is used to collect the incoming incoherent light from objects, which is then passed through a sequentially arranged linear polarizer and a GP lens. After the GP lens, the beam is simultaneously divided into converging and diverging parts. Given that the curvatures of the two beams modulated by the GP lens with the short focal length are relatively large in our system, it is difficult to observe the interference patterns directly and the reconstructed images are also blurry. To enhance the fringe pattern visibility, a relay lens is therefore employed after the GP lens. Finally, a polarization imaging camera is used to record the two-wave interference fringes. The entire optical setup is in-line, simple, and compact. Given the recorded single-shot interferograms, including the information of the four phase-shifted holograms at the polarization directions of 0°, 45°, 90°, and 135°, the complex hologram amplitude and phase data can be extracted using a typical four-step phase-shifting method (24), as shown by Equation (17),

\[
H(x, y) = (I_3 - I_1) - j(I_4 - I_2)
\]

\[
\Delta \phi(x, y) = \tan^{-1} \left( \frac{I_4 - I_2}{I_3 - I_1} \right)
\]  

Figure 2. Reconstruction process of single-shot phase-shifting holograms. (a) Recorded interference pattern image, (b) extraction of each phase shift, and (c) reconstruction of four holograms after the application of a linear interpolation scheme.

Figure 3. Schematic diagram of the single-shot FINCH system in conjunction with the use of a GP lens.
where $I_1$, $I_2$, $I_3$, and $I_4$ in Equation (13) respectively denote the mathematically generated four-step phase-shifted holograms in our camera with different phase values. $H(x, y)$ represents a complex amplitude distribution of incoherent light on the image sensor plane which is reconstructed based on the linear superposition of four holograms. $\Delta \phi(x, y)$ is the phase of the complex hologram. The original object image $S(x, y)$ can then be reconstructed from $H(x, y)$ by calculating the Fresnel propagation formula according to Equation (18),

$$S(x, y) = H(x, y) \ast \exp \left[ -\frac{i \pi}{\lambda z_{\text{rec}}} (x^2 + y^2) \right]$$

where $\ast$ denotes a two-dimensional (2D) convolution operation, and $z_{\text{rec}}$ represents the reconstruction distance.

To experimentally prove our proposed single-shot FINCH, a proof-of-principle setup is constructed, as shown in the photograph in Figure 4. The United States Air Force (USAF) 1951 resolution test chart is used as the imaging target. The system is illuminated by a 530 nm fibre-coupled light emitting diode (LED) (M530F2, Thorlabs) with a spectral bandwidth of $\sim$ 30 nm. A convex lens with a focal length of 100 mm is used to collect the incoming incoherent light after its propagation through the USAF 1951 chart. A linear polarizer is located in front of the GP lens to introduce a linear polarization light to the GP lens. The distance between the GP lens and the convex lens is approximately 80 mm. The GP lens utilized in the system employed herein is an off-the-shelf model (#34–466, Edmund Optics) with a focal length of 100 mm. A polarized sensor (PHX050S–P, LUCID) is located at approximately 120 mm behind the Nikon lens. The pixel number of the image sensor is 2448 × 2048 with a pixel pitch of 3.45 μm. It needs to be noted that a micro-polarizer array is attached to the image sensor on a pixel-by-pixel basis. Four phase-shifted hologram patterns are recorded simultaneously in the four parts of the polarization sensor in every exposure. Furthermore, to investigate the 3D imaging capability of the setup, another 530 nm fibre-coupled LED, and a National Bureau of Standards (NBS) 1963 chart with a 4.5 cycle/mm region are set up normal to each other, and are then combined to the main optical path with a beam combiner, as shown in Figure 4. The distances between USAF 1951 or the NBS 1963 chart and the beam combiner are approximately 30 and 95 mm, respectively.

**Results and discussion**

The interference pattern of the USAF 1951 test chart on the image sensor plane was recorded in a single-shot. The object image was then retrieved using the proposed method. The recorded single-shot hologram of the transmission USAF 1951 resolution test target is shown in Figure 5(a), which shows a nice interference modulation owing to the simple in-line configuration. The four holographic images at the polarization directions of 0°, 45°, 90°, and 135°, obtained by linear interpolation are shown in Figure 5(b–e), which contains increased modulation interference. By using Equation (5) with the four holograms, the complex hologram amplitudes and phases are obtained, as respectively shown in Figure 5(f and g). Finally, an image of the USAF 1951 resolution chart is reconstructed based on the complex hologram amplitude and phase, as shown in Figure 5(h). As a detailed analysis of the red box in Figure 5(h), the intensity profiles of the line pairs shown in Figure 5(i) indicate a clear and deep separation.

One of the most important properties of digital holography is its capability of 3D imaging in single-shot exposures. To verify and explore the 3D imaging capability of our setup, two transmissive targets which are
perpendicular to each other are illuminated separately by the fibre-coupled LED (M530F2, Thorlabs). Each target is aligned with the direction of the beam combiner to represent the volumetric two layer object. The whole USAF 1951 resolution chart region and the NBS 1963 chart with 4.5 cycles/mm region are used to generate the FINCH image. The distance between the two targets is approximately 65 mm. Figure 6 shows the results of holographic acquisition and digital reconstruction of the resolution charts correctly. Figure 6(a) is the recorded single-shot hologram of the transmission resolution test targets. Figure 6(b–e) depicts the four holographic images at the polarization directions of 0°, 45°, 90°, and 135°, respectively. Figure 6(f–g) shows the numerical reconstruction result, where the best of focus on the USAF 1951 and NBS 1963 charts, respectively. The experimental results shown in Figures 5 and 6 have proved the capability of the 3D images of our novel, single-shot FINCH system.

The experimental results are sufficient to prove the capabilities of the proposed incoherent digital holographic recording system. In our system, the phase shift method we used did not depend on the adjustment of the optical path length or phase shifters. Compared with other phase shift methods, such as geometric phase shifting or SLM, the use of the polarization imaging camera with the micro-polarizer array makes the entire optical path simpler and more compact. Moreover, the design of the straight optical path greatly reduces the loss of light intensity. Meanwhile, the use of relay lens enhances the visibility of the interference fringes, but it also limits the numerical aperture of the system. Further reduction of the optical path difference of the entire optical path is necessary to improve the performance of the system.

**Conclusion**

In conclusion, we have proposed a novel single-shot, in-line FINCH system, based on the simultaneous use of a GP lens and a polarization camera. The GP lens had the same technical capability as SLM, and can separate the light into two different wave fronts that make the setup simpler and more economical. The combined use of the polarization imaging camera with the bonding of the micro-polarizer array directly to the sensor, allowed us to achieve a single-shot FINCH system with a compact setup. The designed system was then experimentally
demonstrated based on the recording of standard resolution charts which were illuminated with LEDs. Experimental results showed that the bias and twin images were eliminated with the use of parallel phase-shifting to incoherent digital holography. With further optimization and customization, we believe that the combination of the GP lens with the polarization camera will become a useful contributor for studies in various research fields. More prospective applications can be expected in the near future.

Acknowledgment

The authors would like to thank Prof. Guohai Situ for reading the paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work is supported by the National Natural Science Foundation of China (NSFC) [grant number 61527821, 61521093]; Instrument Developing Project [grant number YZ201538] and the Strategic Priority Research Program [grant number XDB16] of the Chinese Academy of Sciences (CAS); National Natural Science Foundation of China [grant number 11804350]; Shanghai Sailing Program (17YF1421300); National Natural Science Foundation of China [grant number XDB16] of the Chinese Academy of Sciences (CAS); Instrument Developing Project [grant number YZ201538] of the Chinese Academy of Sciences (CAS); Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences.

References

(1) Gabor, D. A New Microscopic Principle. Nature 1948, 161, 777–778.
(2) Poon, T.C. Digital Holography and Three-Dimensional Display: Principles and Applications; Springer: Boston, 2006.
(3) Javidi, B.; Tajahuerce, E. Three-dimensional Object Recognition by Use of Digital Holography. Opt. Lett 2000, 25 (9), 610–612.
(4) Ferraro, P.; Wax, A.; Zalevsky, Z. Coherent Light Microscopy: Imaging and Quantitative Phase Analysis; Springer: Berlin, Heidelberg, 2011.
(5) Indebetouw, G.; El Maghnioui, A.; Foster, R. Scanning Holographic Microscopy with Transverse Resolution Exceeding the Rayleigh Limit and Extended Depth of Focus. J Opt Soc Am A 2005, 22, 892–898.
(6) Rosen, J.; Brooker, G. Non-scanning Motionless Fluorescence Three-Dimensional Holographic Microscopy. Nat Photonics 2008, 2, 190–195.
(7) Shaked, N.T.; Katz, B.; Rosen, J. Review of Three-Dimensional Holographic Imaging by Multiple-View Point Projection Based Methods. Appl. Opt 2009, 48 (34), H120–H136.
(8) Schilling, B.W.; Poon, T.-C.; Indebetouw, G.; Storrie, B.; Shinoda, K.; Suzuki, Y.; Wu, M.H. Three Dimensional Holographic Fluorescence Microscopy. Opt. Lett 1997, 22 (19), 1506–1508.
(9) Rosen, J.; Brooker, G. Digital Spatially Incoherent Fresnel Holography. Opt. Lett 2007, 32 (8), 912–914.
(10) Kashter, Y.; Rosen, J. Enhanced Super Resolution Using Fresnel Incoherent Correlation Holography with Structured Illumination. Opt. Lett 2016, 41 (7), 1558–1561.
(11) Kelnar, R.; Rosen, J. Parallel-mode Scanning Optical Sectioning Using Digital Fresnel Holography with Three-Wave Interference Phase-Shifting. Opt Express 2016, 24 (3), 2200–2214.
(12) Katz, B.; Wulich, D.; Rosen, J. Optical Noise Suppression in Fresnel Incoherent Correlation Holography (FINCH) Configured for Maximum Imaging Resolution. Appl. Opt 2010, 49 (30), 5757–5763.
(13) Siegel, N.; Rosen, J.; Brooker, G. Faithful Reconstruction of Digital Holograms Captured by FINCH Using a Hammering Window Function in the Fresnel Propagation. Opt. Lett 2013, 38 (19), 3922–3925.
(14) Tahara, T.; Kanno, T.; Ozawa, T. Single-shot Phase-Shifting Incoherent Digital Holography. J. Opt 2017, 19, 065705.
(15) Nobukawa, T.; Muroi, T.; Katano, Y.; Kinoshita, N.; Ishii, N. Single-shot Phase-Shifting Incoherent Digital Holography with Multiplexed Checkerboard Phase Gratings. Opt. Lett 2018, 43 (8), 1698–1701.
(16) Zhu, Z.; Shi, Z. Self-interference Polarization Holographic Imaging of a Three-Dimensional Incoherent Scene. Appl. Phys. Lett. 2016, 109 (9), 091104.
(17) Quan, X.; Matoba, O.; Awatsuji, Y. Single-shot Incoherent Digital Holography Using a Dual-Focusing Lens with Diffraction Gratings. Opt. Lett 2017, 42 (3), 383–386.
(18) Choi, K.; Yim, J.; Yoo, S.; Min, S.W. Self-interference Digital Holography with a Geometric-Phase Hologram Lens. Opt. Lett 2017, 42 (19), 3940–3943.
(19) Choi, K.; Yim, J.; Min, S.W. Achromatic Phase Shifting Self-Interference Incoherent Digital Holography Using Linear Polarizer and Geometric Phase Lens. Opt Express 2018, 26 (13), 16212–16225.
(20) Siegel, N.; Lupashin, V.; Storrie, B.; Brooker, G. High-magnification Super-Resolution FINCH Microscopy Using Birefringent Crystal Lens Interferometers. Nat Photonics 2016, 10, 802–808.
(21) Pancharatnam, S. Generalized Theory of Interference, and its Applications. Proc. Indian Acad. Sci. - Sect. A 1956, 44, 247–262.
(22) Hornburg, K.J.; Kim, J.; Escuti, M.J. Experimental Characterization of a F/1.5 Geometric-Phase Lens with High Achromatic Efficiency and Low Aberration. Proc. SPIE. 2017, 10125, 101250Y-1–101250Y-8.
(23) Yamaguchi, I.; Zhang, T. Phase-shifting Digital Holography. Opt. Lett 1997, 22 (16), 1268–1270.
(24) Awatsuji, Y.; Sasada, M.; Kubota, T. Parallel Quasiphase-Shifting Digital Holography. Appl. Phys. Lett. 2004, 85 (6), 1069–1071.
(25) Kakue, T.; Yonesaka, R.; Tahara, T.; Awatsuji, Y.; Nishio, K.; Ura, S.; Kubota, T.; Matoba, O. High-speed Phase Imaging by Parallel Phase-Shifting Digital Holography. Opt. Lett 2011, 36 (21), 4131–4133.