[Invited] High-speed/ultrafast holographic imaging using an image sensor

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Abstract This paper reviews two holographic techniques studied by the group of the authors. One is a technique for three-dimensional imaging of high-speed and transparent object. A 3-D motion picture of transparent gas flow was demonstrated. Also, a movie of ultrasound propagation was demonstrated. The other is a technique for ultrafast imaging of light pulse propagation. A motion picture of a light pulse propagating in a light scattering medium was demonstrated. Each technique uses an image sensor to record motion picture of holograms and numerically reconstructs the motion picture of the object.

Keywords: holography, digital holography, high-speed imaging, ultrafast imaging, light propagation

1. Introduction

Holography is a technique to record and reconstruct perfect wavefronts of objects and it is famous for three-dimensional (3-D) display. A hologram is a medium in which 3-D information of an object is recorded; photosensitive materials such as photographic plates are generally used to record holograms. There has been a great deal of progress in image sensors such as charge-coupled devices (CCDs) and complementary metal-oxide semiconductor image sensors (CMOSs), and such devices have been in holography in place of the conventional recording medium. Holography using an image sensor is called digital holography [1]. Digital holography reconstructs the image of an object by computer, and therefore has the following attractive features: motion picture of holograms can be recorded, quantitative evaluation is easy for 3-D images of objects; and focused images of 3-D objects at desired depth can be instantaneously acquired without a mechanical focusing process.

As a digital holography capable of high-speed imaging of dynamic object, the we introduce parallel phase-shifting digital holography. We describe the principle of parallel phase-shifting digital holography [2,3] and a parallel phase-shifting digital holography system using a high-speed polarization imaging camera [4,5]. Also, we describe applications of the system to high-speed 3-D imaging of transparent gas flow and motion picture recording of ultrasound propagation [6].

As a digital holography capable of ultrafast imaging of light propagation, the we introduce digital light-in-flight recording by holography [7-9]. We describe the principle of digital light-in-flight recording by holography and an application of the technique to recording ultrafast video of light pulse propagating a light scattering medium [10].
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2. Parallel phase-shifting digital holography and parallel phase-shifting digital holography system using a high-speed polarization camera#

Figure 1 shows a schematic of the principle of parallel phase-shifting digital holography [2,3]. Multiple holograms required for phase-shifting digital holography [11] are multiplexed into a single hologram by using space-division multiplexing of holograms. The single hologram is recorded by a single image sensor with a single exposure. The recorded single hologram is demultiplexed into multiple phase-shifted holograms. The blanked pixels in the phase-shifted holograms are interpolated by computer. The scheme of the conventional phase-shifting digital holography is applied to the interpolated phase-shifted holograms. Then the complex amplitude of the object is reconstructed. Neither the non-diffraction wave nor the conjugate image is superimposed on the reconstructed image. Therefore, this technique can be applied to single-shot recording of the complex amplitude of the object wave and measurement of dynamic and transparent objects.

A schematic of the parallel phase-shifting digital holographic system using a high-speed polarization imaging camera [4-6] is shown in Fig. 2. This system consists of a Mach–Zehnder interferometer and a high-speed polarization-imaging camera [12]. As shown in Fig. 2, each 2×2-pixel configuration of the image sensor of the camera can simultaneously detect the intensity of four linear-polarization components of the laser beam incident to the image sensor. An interference fringe image is generated by the object wave and the reference wave in the same linear-polarization direction of the image sensor. Four pixels with phase-shifts of 0, $-\pi/2$, $-\pi$, and $-3\pi/2$ are extracted from each 2×2-pixel configuration in order to carry out the numerical processing employed in parallel phase-shifting digital holography. Thus, high-speed phase-shifting interferometry at the same frame rate of the camera is achieved. A $Nd:YVO_4$ laser operated at 532 nm were used for the optical source. #
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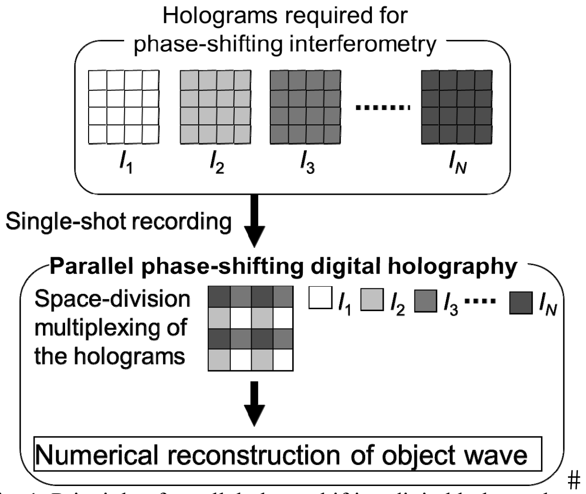

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Fig. 1. Principle of parallel phase-shifting digital holography.
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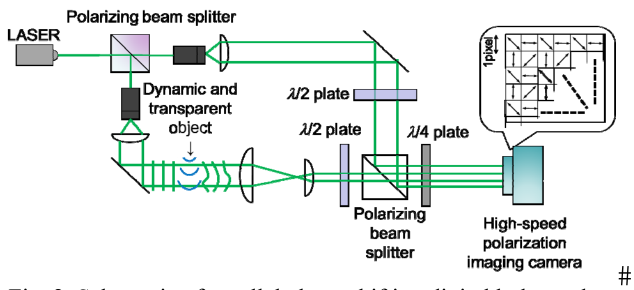

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Fig. 2. Schematic of parallel phase-shifting digital holography system using a high-speed polarization-imaging camera.
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3. High-speed 3-D imaging of transparent gas flow

To demonstrate 3-D imaging capability of dynamic and transparent object of the system, transparent gas flow sprayed from a nozzle was recorded [6]. FASTCAM-SA2-P (Photron Ltd.) was employed for the high-speed polarization imaging camera. A motion picture of hologram was recorded at 3000 fps. A photograph and a schematic of the object are shown in Fig. 3. To derive the 3-D image of the gas flow, Abel inversion [13] was applied to the phase image obtained by parallel phase-shifting digital holography. The obtained 3-D distribution of the refractive index of the gas flow was obtained from the hologram as shown in Fig. 4. #
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4. High-speed video of ultrasound propagation

As another demonstration of imaging capability of dynamic and transparent object of the system, ultrasound propagation was recorded [14-16]. FASTCAM-SA5-P (Photron Ltd.) and MA40S4S (Murata Manufacturing Co., Ltd.) were used for the high-speed polarization-imaging camera and the sound source, respectively. The sound source launched a 40,000 Hz wave. A sequence of the holograms of the ultrasound was recorded at 100,000 frames per second for 5 ms.

Because the temporal change in phase image caused by the ultrasound was much smaller than that of air disturbance around the measuring area, it was difficult to recognize the sound propagation from the phase image of the object. Then we derived the phase-difference image by temporally differentiating the sequence of the phase images. Figure 5 shows the phase-difference images derived from the sequence of the holograms. As seen from Fig.5, the sound wave propagated as the same distance as the wavelength of the sound during 2.5 frames in the phase difference images. Thus, we successfully recorded the motion picture of the 40,000 Hz sound wave propagation.

We measured the frequency spectrum from the sequence of the phase images. Figure 6 shows the frequency spectrum at a point in the phase image. As seen from the figure, we successfully measured the frequency from the phase images.
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Fig. 3. Object, transparent gas flow sprayed from a nozzle. (a) Photograph, (b) schematic.

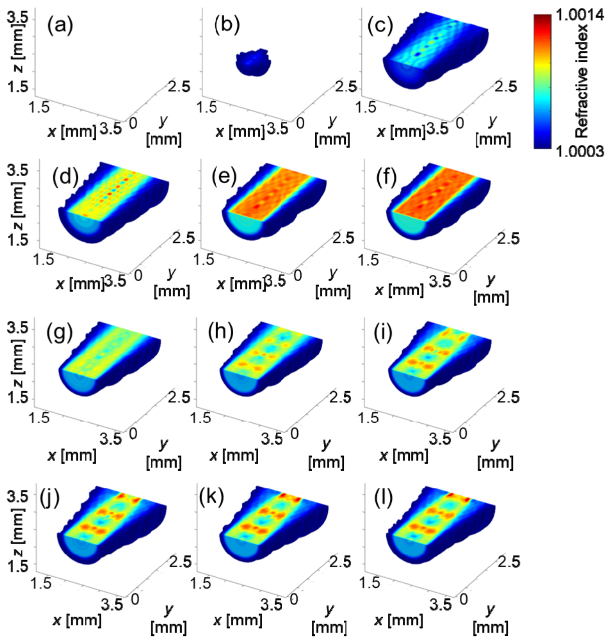

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Fig. 4. 3-D imaging of compressed gas flow obtained by the high-speed parallel phase-shifting digital holography system. Time intervals between the neighboring image were 2 ms and 10 ms for (a)-(f) and (g)-(l), respectively.
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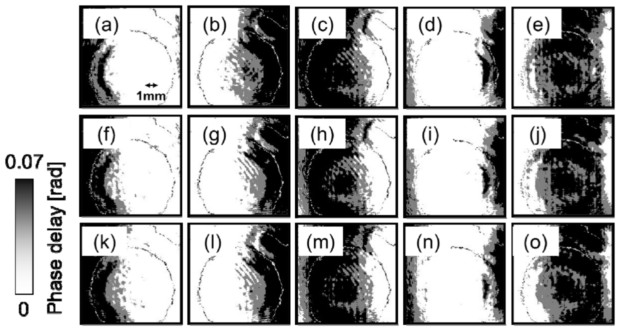

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Fig. 5. Phase difference images of ultrasound propagation reconstructed from the recorded holograms at 100,000 fps. Time interval between the neighboring image was 10 μs.

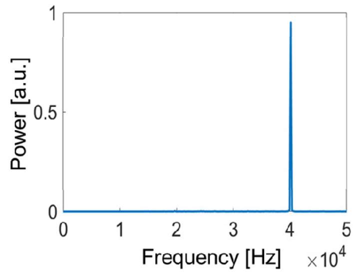

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Fig. 6. Frequency spectrum obtained from the sequence of the phase images reconstructed by the system.
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5. Digital light-in-flight recording by holography

Light-in-flight recording by holography [17-20] is a technique capable of recording a motion picture of light pulse propagation. The technique uses an ultrashort pulsed laser for the optical source of the recording process of holography. In particular, a technique using an image sensor to record the hologram and a computer to reconstruct the image from hologram in light-in-flight recording by holography is called as digital light-in-flight recording by holography [7-9]. Figure 7 shows a schematic of the basic arrangement of the digital light-in-flight recording by holography. A light pulse emitted from the ultrashort pulsed laser is divided into two light pulses. The two light pulses are collimated. One collimated pulse is obliquely incident to the image sensor, and this pulse is called as the reference light pulse. The other is also obliquely incident to the diffuser plate contacted with the object. The light pulse scattered by the diffuser is called as the object pulse. Interference fringe is generated only where both the object light pulse and the reference light pulse simultaneously arrive on the image sensor. In order to reconstruct the image of the light pulse from the digitally recorded hologram, the recorded hologram is horizontally divided into many pieces. The piece is called as the sub-hologram. By applying the same numerical reconstruction process to each sub-hologram, as digital holography, each moment of the image of the propagating light pulse is reconstructed. When the reconstructed image is sequentially displayed, the motion of the propagating light pulse is replayed. #
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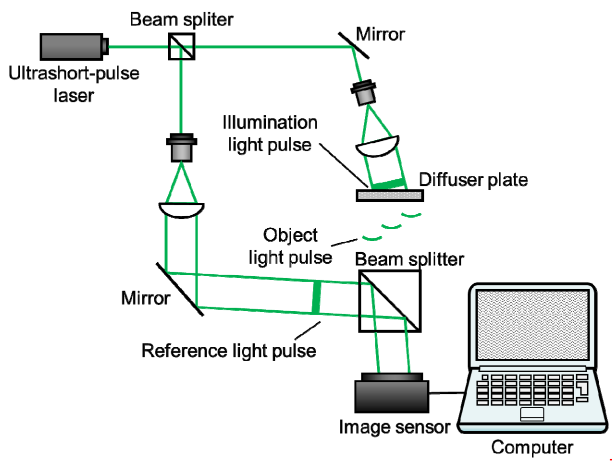

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Fig. 7. Schematic of the basic optical setup for recording the hologram of digital light-in-flight recording by holography#

6. Ultrafast movie of a light pulse propagating in a light scattering medium

We applied digital light-in-flight recording by holography to record and observe a motion picture of a light pulse propagating in a light scattering medium [10]. To record the motion picture, we replaced the diffuser plate shown in Fig. 7 with a voluminous light-scattering medium. The voluminous light-scattering medium was made of gelatin jelly stuffed in a transparent container. The container was set at an angle of 45° to the surface of the image sensor. A diffraction grating is inserted into the path of the reference light pulse to extend the recordable time of the motion picture. A light pulse diffracted from the diffraction grating was used as the tilted reference light pulse. The tilted reference pulse was obliquely incident on the image sensor.#A mode-locked $Yb:YVO_4$ pulsed laser (HighQ-2 SHG, Spectra-Physics Inc.) was used for the light source. The center wavelength and the duration of the light pulses emitted from the laser were 522 nm and 178 fs, respectively. We used a digital CCD camera (OLCA-HR, Hamamatsu Photonics K. K.) to record the hologram. The number of pixels and the pixel pitch of the camera were 4000 (H) × 2624 (V) pixels and 5.9 μm × 5.9 μm, respectively. #

To record the propagation of a converging light pulse, a convex lens with a diameter of 4 cm and a focal length of 6 cm was placed just before the container. Figure 8 shows the frames extracted from the motion picture. We reconstructed the image of each moment from 512 × 512 pixels extracted from the sub-hologram. The actual duration of the motion picture was 59 ps, and the time interval between adjacent images was 10 ps. The bright parts in Fig. 8 are the reconstructed images of the converging light pulse. The frame rate of the obtained motion picture was 68 Tfps.
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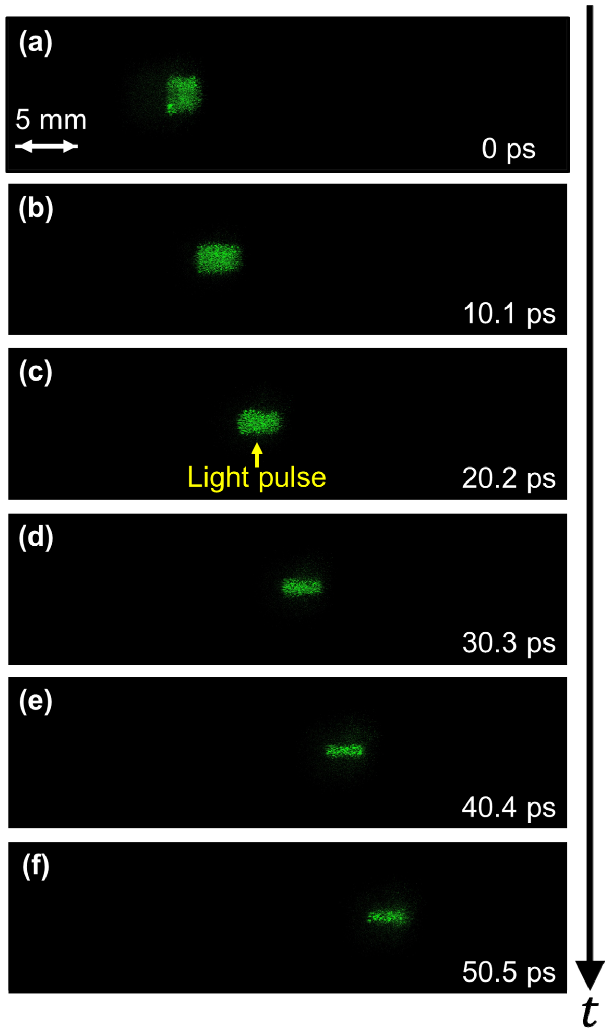

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Fig. 8. Frames extracted from the motion picture of the reconstructed image of the converging light pulse in the gelatin jelly.

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7. Summary

We reviewed two kinds of digital holography; parallel phase-shifting digital holography and digital light-in-flight recording by holography. The former will contribute to many fields such as flow measurement, particle measurement, living cell observation, micro-deformation measurement in production inspection. The latter will contribute to the frontier of natural sciences to elucidate and discover ultrafast phenomena in physics, chemistry, and biology.

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References

[1] J. W. Goodman and R. W. Lawrence, “Digital image formation from electronically detected holograms,” Appl. Phys. Lett., Vol.11, No.3, pp.77-79 (1967).

[2] Y. Awatsuji, M. Sasada, and T. Kubota, "Parallel quasi-phase-shifting digital holography," Appl. Phys. Lett., Vol. 85, No. 6, pp.1069-1071 (2004).

[3] T. Tahara, K. Ito, M. Fujii, T. Kakue, Y. Shimozato, Y. Awatsuji, K. Nishio, S. Ura, T. Kubota, and O. Matoba, "Experimental demonstration of parallel two-step phase-shifting digital holography,” Opt. Express, Vol.18, No.18, pp.18975-18980 (2010).

[4] T. Kakue, R. Yonesaka, T. Tahara, Y. Awatsuji, K. Nishio, S. Ura, T. Kubota, and O. Matoba, "High-speed phase imaging by parallel phase-shifting digital holography," Opt. Lett., Vol.36, No.21, pp.4131-4133 (2011).

[5] P. Xia, Y. Awatsuji, K. Nishio, and O. Matoba, "One million fps digital holography," Electron. Lett., Vol.50, No.23, pp.1693-1695 (2014).

[6] T. Fukuda, Y. Wang, P. Xia, Y. Awatsuji, T. Kakue, K. Nishio, and O. Matoba, "Three-dimensional imaging of distribution of refractive index by parallel phase-shifting digital holography using Abel inversion," Opt. Express, Vol.25, No.15, pp.18066-18071 (2017).

[7] J. Pomarico, U. Schnars, H.-J. Hartmann, and W. Jüptner, "Digital recording and numerical reconstruction of holograms: a new method for displaying light in flight," Appl. Opt., Vol.34, No.35, pp.8095–8099 (1995).

[8] B. Nilsson and T. E. Carlsson, "Direct three-dimensional shape measurement by digital light-in-flight holography," Appl. Opt., Vol.37, No.34, pp.7954–7959 (1998).

[9] T. Kakue, K. Tosa, J. Yuasa, T. Tahara, Y. Awatsuji, K. Nishio, S. Ura, and T. Kubota, "Digital light-in-flight recording by holography by use of a femtosecond pulsed laser," IEEE J. Sel. Topics Quantum Electron., Vol.18, No.1, pp.479-485 (2012).

[10] T. Inoue, Y. Junpei, S. Itoh, T. Okuda, A. Funahashi, T. Takimoto, T. Kakue, K. Nishio, O. Matoba, and Y. Awatsuji, "Spatiotemporal observation of light propagation in a three-dimensional scattering medium," Sci. Rep., Vol. 11, 21890 (2021).

[11] I. Yamaguchi and T. Zhang, “Phase-shifting digital holography,” Opt. Lett., Vol.22, No.16, pp.1268-1270 (1997).

[12] T. Onuma and Y. Otani, “A development of two-dimensional birefringence distribution measurement system with a samplsing rate of 1.3 MHz,” Opt. Commun., Vol.315, pp.69-73 (2014).

[13] K. Bockasten, “Transformation of observed radiances into radial distribution of the emission of a plasma,” J. Opt. Soc. Am., Vol. 51, No.9, pp.943-947, (1961).

[14] Y. Takase, K. Shimizu, S. Mochida. T. Inoue, K. Nishio, S. K. Rajput, O. Matoba, P. Xia, and Y. Awatsuji, "High-speed imaging of the sound field by parallel phase-shifting digital holography," Appl. Opt., Vol.60, No.4, pp.A179-A187 (2021).

[15] S. K. Rajput, O. Matoba, Y. Takase, T. Inoue, K. Itaya, M. Kumar, X. Quan, P. Xia, and Y. Awatsuji, "Multimodal sound field imaging using digital holography," Appl. Opt., Vol.60, No.10, pp.B49-B58 (2021).

[16] S. Hashimoto, Y. Takase, T. Inoue, K. Nishio, P. Xia, S. K. Rajput, O. Matoba, and Y. Awatsuji, "Simultaneous imaging of sound propagations and spatial distribution of acoustic frequencies," Appl. Opt., Vol.61, No.5, pp.B246-B254 (2022).

[17] D. I. Staselko, Yu. N. Denisyuk, and A. G. Smirnov, “Holographic registration of a picture of temporal coherence of a wave train of a pulse radiation source,” Opt. Spectrosc., Vol.26, pp.413-420, (1969).

[18] N. Abramson, “Light-in-flight recording: by holography,” Opt. Lett., Vol.3, No.4, pp.121-123 (1978).

[19] T. Kubota and Y. Awatsuji, "Observation of light propagation by holography with a picosecond pulsed laser," Opt. Lett., Vol. 27, No. 10, pp.815-817 (2002).

[20] T. Kubota, K, Komai, M. Yamagiwa, and Y. Awatsuji, "Moving picture recording and observation of three-dimensional image of femtosecond light pulse propagation," Opt. Express, Vol.15, No.22, pp.14348-14354 (2007).