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Algorithm for extracting multiple object waves without Fourier transform from a single image recorded by spatial frequency-division multiplexing and its application to digital holography

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ABSTRACT

We propose a novel algorithm that does not require any Fourier transform to extract multiple object waves in a single image recorded with spatial frequency-division multiplexing. Smoothing is utilized to extract the desired object-wave information from a spatially multiplexed image. Numerical and experimental results show its validity and applicability for image and Fresnel digital holography. Our investigations clarify the speeding up of both the object-wave extractions and multiple object–image reconstructions quantitatively.

1. Introduction

Digital holography [1,2] is a three-dimensional (3D) imaging technique using interference and diffraction of light. The technique obtains a complex amplitude distribution of an object wave with an image sensor and displays a natural 3D image with a computer or a spatial light modulator. Not only 3D space but also a quantitative phase image of the object are obtained via numerical calculation of the object-wave propagation. The technique has been actively researched in the fields of microscopy [3], quantitative phase imaging of cells [4], optical sectioning imaging [5], multimodal imaging [6], multidimensional imaging with a single pixel [7], simultaneous encryptions of multiple 3D images [8], speckle-less 3D image sensing for display [9], high-speed 3D image reconstruction [10], and ultrafast photonics [11]. In holography and digital holography, information such as wavelengths, state of polarization, and multiple phases is obtained simultaneously on spatially multiplexed image(s) by utilizing spatial frequency-division multiplexing [12–15], temporal frequency-division multiplexing [16,17], or phase-division multiplexing [18–20]. By using spatial frequency-division multiplexing, the information of each object wave is localized in a different region from each other in the spatial frequency domain, and separately extracted from a hologram by Fourier fringe analysis [21]. Therefore, multidimensional imaging is conducted without the crosstalk between object waves from a single multiplexed hologram and high-speed multidimensional motion-picture recording can be achieved. However, conventionally, digital holography with spatial frequency-division multiplexing requires a long time to reconstruct multiple images from a recorded hologram. This is because the calculations of 2D Fourier/inverse Fourier transforms are needed, based on the Fourier fringe analysis. If there is an algorithm to reconstruct multiple object waves with a low computational cost, holographic motion-picture image reconstruction with high throughput can be achieved without any high-performance computers.

In this article, we propose a novel algorithm that does not require any Fourier transform to extract multiple object waves in a single image recorded by spatial frequency-division multiplexing. Smoothing is utilized for a multiplexed hologram to selectively extract an object wave that is localized in the spatial frequency domain. Holographic image reconstruction with high throughput is expected when applied to digital holography because no Fourier transform is used for object-waves extraction. Its validity and effectiveness are numerically and experimentally confirmed.

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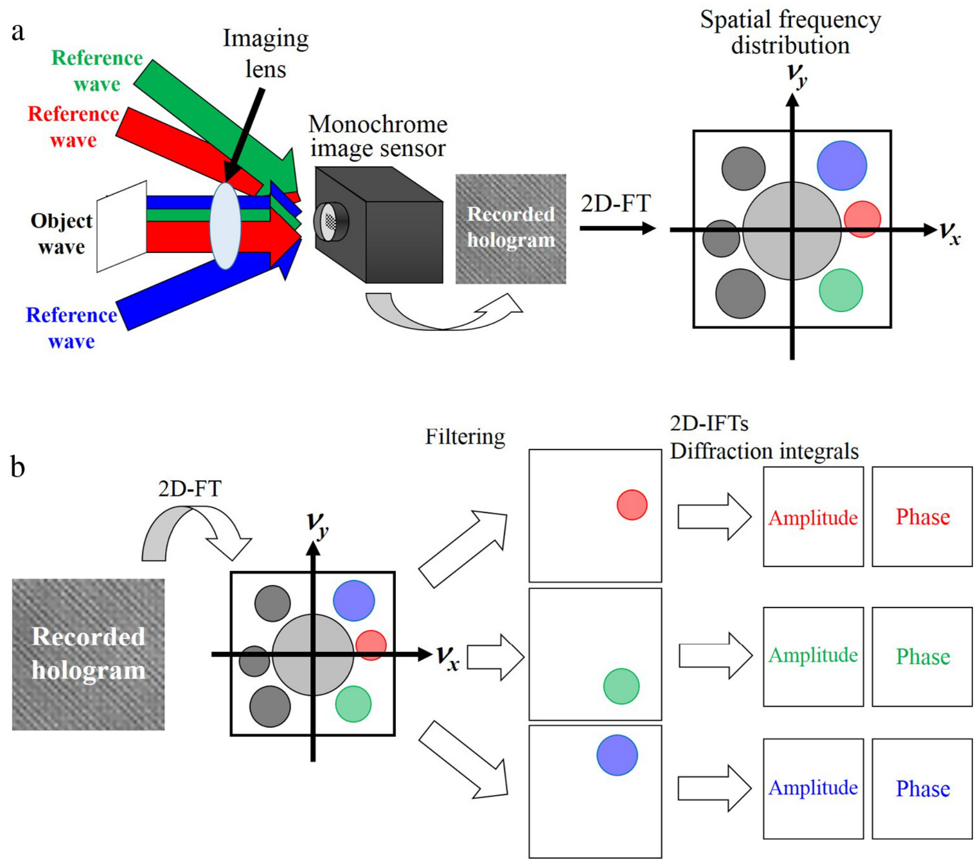

Fig. 1. Schematic of multiplexed digital holography using spatial frequency-division multiplexing. (a) A recording setup and a spatially multiplexed hologram. (b) Conventional image-reconstruction algorithm.

2. Principle

Fig. 1 shows a schematic of digital holography using spatial frequency-division multiplexing [12–15] in the case where the number of object waves M is three. Fig. 1(a) illustrates the schematic of a recording system in the digital holographic technique. The spatial frequency of each object wave is modulated by introducing a different spatial carrier frequency. Spatial carrier frequency depends on the angle between object and reference waves θ [12,13] and the wavelength used for the recording λ [14]. The period of interference fringes Λ and its spatial frequency ν are expressed as follows.

$$\Lambda = \lambda / \sin\theta, \tag{1}$$

$$\nu = 1/\Lambda = \sin\theta/\lambda. \tag{2}$$

ν is determined by λ and θ, and therefore spatial frequency spectra of object waves are separated in the spatial frequency domain by changing λ and θ. As a result, the desired object wave is easily extracted from a multiplexed hologram in the spatial frequency domain by using the Fourier transform method [21], as shown in Fig. 1(b). However, multiple 2D Fourier/inverse Fourier transforms are required to extract multiple object-wave spectra from the hologram, which then takes significantly more time to reconstruct object waves due to the requirement of 2D Fourier/inverse Fourier transforms.

Fig. 2 illustrates the procedure of the proposed algorithm. No Fourier transform is calculated when extracting the object waves separately from a spatially multiplexed hologram. It is expected that the proposal achieves the acceleration of image reconstruction due to the use of only simple signal processing in the space domain. Where $H(x,y)$ is a recorded image, $I_m(x,y)$ is a hologram containing an object wave $U_{om}(x,y)$ and reference wave $U_{rm}(x,y)$, m is an integer from 1 to M, A is an amplitude, ϕ is a phase, i is an imaginary unit, and * is a complex conjugate, a wavelength-multiplexed hologram $H(x,y)$ is expressed as follows.

$$H(x,y) = \sum_{m=1}^{M} I_m(x,y), \tag{3}$$

$$I_m(x,y) = |U_{om}(x,y)|^2 + |U_{rm}(x,y)|^2 + U_{om}(x,y)U_{rm}(x,y)^* + U_{om}(x,y)^* U_{rm}(x,y), \quad (n = 1, \ldots, M) \tag{4}$$

$$U_{om}(x,y) = A_{om}(x,y)\exp\{i\phi_{om}(x,y)\}, \tag{5}$$

$$U_{rm}(x,y) = A_{rm}(x,y)\exp\{i\phi_{rm}(x,y)\}. \tag{6}$$

If $\exp\{i\phi_{rm}(x,y)\}$ is multiplied to Eq. (4) to remove a spatial carrier frequency from the third term of the right-hand side, only $U_{om}(x,y)$ is localized on the low spatial frequency region. In the same manner, when $M = 3$ and $\exp\{i\phi_{r1}(x,y)\}$, $\exp\{i\phi_{r2}(x,y)\}$, or $\exp\{i\phi_{r3}(x,y)\}$ is multiplied to Eq. (3) to remove a spatial carrier generated by each reference beam, $U_{o1}(x,y)$, $U_{o2}(x,y)$, or $U_{o3}(x,y)$ is moved to the low spatial frequency. Then, a smoothing process such as mean filter is applied to a multiplexed hologram with the removal of the spatial carrier. This procedure is conducted because only the desired object-wave component is localized in the low spatial frequency region and is selectively extracted in the space domain by smoothing. Iterative calculation of smoothing is conducted to effectively extract an object wave from a multiplexed image. After that, only the desired object-wave component is obtained. By repeating the removal of the spatial carrier of the object wave and smoothing process to the hologram with no spatial carrier on the desired object wave, multiple object waves are separately and selectively obtained. As a result, multiple object waves are extracted without a Fourier transform from a hologram. Although indeed 2D