Complex-amplitude Fourier single-pixel imaging via coherent structured illumination

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We propose a method of complex-amplitude Fourier single-pixel imaging (CFSI) with coherent structured illumination to acquire both the amplitude and phase of an object. In the proposed method, an object is illustrated by a series of coherent structured light fields which are generated by a phase-only spatial light modulator, the complex Fourier spectrum of the object can be acquired sequentially by a single-pixel photodetector. Then the desired complex-amplitude image can be retrieved directly by applying an inverse Fourier transform. We experimentally implemented this CFSI with several different types of objects. The experimental results show that the proposed method provides a promising complex-amplitude imaging approach with high quality and a stable configuration. Thus, it might find broad applications in optical metrology and biomedical science.

I. INTRODUCTION

An optical field is expressed as a complex-amplitude, which describes both the amplitude and phase of the light wave. Conventional imaging only observes amplitude information, but the important phase information is lost. This is because from the photodetector to the human retina only respond to light intensity. Developing an efficient approach to recover full complex-amplitude of an optical field has been one of the most attractive challenges in modern imaging science. Starting with early Zernike’s phase contrast microscopy [1], various complex-amplitude imaging techniques have been proposed, such as differential interference contrast microscopy [2], Shack-Hartmann sensing [3], coherent diffraction imaging [4], digital holography [5], Fourier ptychographic microscopy [6], lensless ghost imaging [7–9], and phase imaging techniques based on transport-of-intensity equation [10].

However, almost all the above methods require pixelated imaging sensors. This leads to a strong challenge for the cases with a light of invisible wavelength or extremely low intensity. Because it can be impractical or prohibitively costly to implement with a pixelated imaging device. Single-pixel imaging (SPI), as an emerging imaging technique characterized by using structured illumination and a single-pixel detector, has the potential to overcome the challenge [11]. Thus, several attempts were made to achieve the complex amplitude information of objects by using SPI techniques, such as single-pixel diffractive imaging [12–14], single-pixel wavefront sensing [15–17], single-pixel ptychography [18], single-pixel digital holography [19–24], and single-pixel phase imaging based on common-path interferometry [25–30].

Benefiting from the advantages of single-pixel detectors, the complex-amplitude single-pixel imaging is becoming a promising imaging modality in the fields of optical microscopy [25], optical metrology [29], and biomedical science [24].

In this letter, we present a novel complex-amplitude Fourier single-pixel imaging (CFSI) method by combining coherent structured illumination [14, 20, 25, 27, 29] and common-path interference [25–30] with Fourier basis scan [31–34]. Different from previous CFSI methods [22, 27, 28] that use the digital micromirror device based on the super-pixel method for complex-amplitude modulation, we employ a phase-only spatial light modulator to generate both the structured light and the reference light to form the coherent structured illumination. The phase modulation proposal is relatively simple and efficient. Compared to a two-beam interferometer, the single-beam structure is more compact and stable in practical application. With the help of a 4-step phase-shifting, the complex-valued Fourier spectrum can be directly acquired by single-pixel detection. The desired complex-amplitude image can be further retrieved by applying an inverse Fourier transform. In the experiments, the proposed CFSI is implemented with three different types of objects. Experimental results demonstrate that the coherent structured illumination enable the CFSI method to have high quality and a stable configuration. In addition, we find that the undersampling technique can effectively remove noise and considerably accelerate the image acquisition process in our CFSI scheme.

II. METHODS

A. Schematic of our CFSI

The schematic of our CFSI is depicted in Fig. 1. A He-Ne laser of wavelength 632.8 nm is first expanded and collimated by a spatial filter (SF) and a collimating lens (L1), then passes through a beam splitter (BS), and finally incident on a phase-only liquid-crystal-on-silicon spatial
light modulator (LCoS-SLM). Since the modulation efficiency of the LCoS is not 100%, the reflected light consists of two parts, the phase-modulated structured light and the directly reflected light that serves as the reference light. The structured light and the reference light travel along the same path, resulting in common-path interference to form coherent structured illumination. The structured light and the reference light interfere to form coherent structured illumination. The Fourier spectrum of the transmitted object light is obtained by taking the inverse discrete Fourier transform (IDFT) to facilitate the inverse discrete Fourier transform (IDFT) to reconstruct the complex transmittance of the target object.

Then the Fourier spectrum coefficient $F(u, v)$ can be obtained by

$$F(u, v) = \langle f, T_{uv}^* \rangle_F,$$

where $\langle \cdot, \cdot \rangle_F$ denotes the Frobenius inner product, and $^*$ denotes complex conjugate. Each Fourier spectrum coefficient can be acquired one by one, hence this technique is called Fourier basis scan.

From the definition of Eq. (3), it can be seen that the Fourier basis matrix $T_{uv}$ is a phase-only matrix with the phase distribution of $\arg T_{uv} \in [0, 2\pi)$. Using the phase distribution, we can generate a phase pattern

$$P_{uv} = \frac{1}{2\pi} \arg T_{uv}.$$

We load the LCoS with the phase pattern $P_{uv}$ to generate the corresponding structured light, which has the form of $E_0T_{uv}$, where $E_0$ is the amplitude of the structured light. The reference light can be expressed as $E_r e^{-j\phi_r}$, where $E_r$ is the amplitude and $\phi_r$ is the initial phase. Thus, the coherent structured illumination has the form of

$$E_{uv} = E_0T_{uv} + E_r e^{-j\phi_r} \mathbf{1},$$

where $\mathbf{1}$ denotes a matrix of ones which has the same dimension as $T_{uv}$. Under this coherent structured illumination, the zero-frequency component of the object light measured by PMT can be expressed as

$$D(u, v) = \eta |\langle f, E_{uv}^* \rangle_F|,$$

where $\eta$ represents the quantum efficiency of PMT.
of phase-shifted basis matrices $T_{uv}^{(\varphi)} = e^{j\varphi}T_{uv}$. The corresponding phase patterns are generated by $P_{uv}^{(\varphi)} = \arg T_{uv}^{(\varphi)}/2\pi$, as shown in the inset of Fig. 1. We load the whole set of the phase patterns $\{P_{uv}^{(\varphi)}\}$ onto the LCoS one by one and acquire the corresponding responses of PMT, denoted as $\{D_{uv}^{(\varphi)}(u, v)\}$. Then we can retrieve the Fourier spectrum matrix of the target object from the responses of PMT as

$$F = \alpha \left\{ \left[ D_{uv}^{(0)} - D_{uv}^{(\pi)} \right] + j \left[ D_{uv}^{(3\pi/2)} - D_{uv}^{(\pi/2)} \right] \right\}, \quad (8)$$

where $\alpha$ is a complex constant. By using the IDFT, we can reconstruct the complex transmittance of the target object

$$f = \text{fftshift}\{\text{ifft2}(F)\}, \quad (9)$$

where $\text{ifft2}\{\cdot\}$ denotes the two-dimensional IDFT operation using a fast algorithm and the subsequent $\text{fftshift}\{\cdot\}$ operation shifts the coordinate origin to the center of the matrix.

III. RESULTS

In all experiments, we set the imaging resolution to $128 \times 128$ pixels, and display each pixel of the phase patterns as $2 \times 2$ LCoS pixels. Since the effective aperture is large enough, all the coherent structured illumination patterns can be imaged onto the object by the $4f$ system. As the pixel pitch of the LCoS is 8 $\mu$m and the magnification of the $4f$ system is 1/3, the spatial resolution and the field of view of this CFSI are theoretically 5.33 $\mu$m and 682.67 $\mu$m in the experiments.

As a demonstration, we first apply our CFSI to image a glass plate etched with three intersecting discs. As shown in Fig. 2(a), the discs are all 400 $\mu$m in diameter, and the circumference of each disc passes through the centers of the other two discs. The etching depths in red, green and blue regions are 372 nm, 715 nm, and 1051 nm, respectively. This is a simple phase object. Fig. 2(b) shows the macro photo of this etched object captured by a digital camera. Fig. 2(c) shows the theoretical phase distribution of this etched object for the light of wavelength 632.8 nm, and the phase profile along the highlighted line is shown in Fig. 2(d).

Fig. 2(e) shows the magnitude of the measured spectrum. The values of the measured spectrums are linearly scaled to $[0, 1]$, but the dynamic range of the spectrum is compressed to show the high frequency components more clearly. The reconstructed amplitude and phase images are shown in Figs. 2(f) and (g), respectively, and the phase profile along the highlighted line is shown in Fig. 2(h). The values of the reconstructed amplitude images are linearly scaled to $[0, 1]$ for display. Due to the phase modulation error of LCoS-SLM, external vibration and other factors, the measured spectrum contains noises, which affect the reconstructed image quality. The low frequency noises cause a bright dot in the center of the reconstructed amplitude image, as shown in Fig. 2(f). The high frequency noises, which can be seen as symmetric pairs of bright dots in the magnitude spectrum shown in Fig. 2(e), cause the reconstructed phase fluctuation, as shown in Fig. 2(h). At full sampling ratio, the imaging acquisition time is 195 minutes, which is mainly limited by the response time and phase flicker of LCoS-SLM.

The high frequency noises can be avoided by undersampling. Here we set the sampling ratio of 17.2%, at which point the high frequency noises basically disappears, as shown in Fig. 2(i). In addition, undersampling can significantly reduce the acquisition time. At the current sampling ratio, the imaging acquisition time is about 34 minutes. To eliminate the influence of low frequency noises, we need perform noise suppression during image reconstruction, similar to that proposed by Xiao et al. in reference[35]. We use the subimage within the $3 \times 3$ neighborhood of the center of the reconstructed image as an estimate of the spectrum of the low frequency noises in all experiments. The final reconstructed amplitude and phase images are shown in Figs. 2(j) and (k), respectively, and the phase profile along the highlighted line is shown in Fig. 2(l). It can be seen that the reconstructed image after noise reduction has clear amplitude and smooth and accurate phase.

In the second experiment, we challenge our CFSI with a detailed phase object, which is a glass plate etched with
the logo of Hebei University. As shown in Fig. 3(a), the diameter of the logo is 600 µm, and the etching depths in the red, green and blue regions are 372 nm, 715 nm, and 1051 nm, respectively. Fig. 3(b) shows the macro photo of this etched object captured by a digital camera. Fig. 3(c) shows the theoretical phase distribution of this etched object for the light of wavelength 632.8 nm, and the phase profile along the highlighted line is shown in Fig. 3(d).

In this case, to preserve as much details as possible, we set the sampling ratio to 47.9%. The imaging acquisition time is about 257 minutes. Fig. 3(e) shows the magnitude of the measured spectrum. The reconstructed amplitude and phase images are shown in Figs. 3 (f) and (g), respectively, and the phase profile along the highlighted line is shown in Fig. 3(h). It can be seen that the reconstructed amplitude image shown in Fig. 3(f) matches very well with the macro photo given in Fig. 3(b). As seen in Figs. 3(g) and 3(h) the reconstructed phase image using this CFSI are clear and accurate. However, there is a loss of some details in the reconstructed images, for example, the Chinese characters in the central region of the logo. This is due to insufficient spatial resolution in the experiment.

In the third experiment, we use a damselfly wing as the target object, to test the imaging capability of this CFSI method for natural biological tissues. We use this CFSI method to image the wing in the red box region, as shown in Fig. 4(a), and the reconstructed amplitude and phase images are shown in Figs. 4(b) and 4(c), respectively. The corresponding three-dimensional surface of the phase image is shown in Fig. 4(d). With the phase distribution, we can obtain more information about the wing. Due to less details, here we set the sampling ratio to 17.2%. In this case, the image acquisition time is about 34 minutes.

Due to vibration, lens aberrations, etc. the achievable spatial resolution is larger than the theoretical value of 5.33 µm in practice. In the fourth experiment, we use the negative USAF-1951 resolution test chart as the target object to quantify the achievable spatial resolution in the experiments. The experimental results are shown in Fig. 5, where (a) and (b) show the amplitude image and phase image, respectively. The amplitude profiles along the highlighted lines across the horizontal and vertical bars of group 6 element 3 are shown in the left and top subplots, respectively, where the axes along the image
represent the pixel positions and each dot represents the amplitude value of one pixel. The corresponding phase profiles are also given in Fig. 5(b). As shown in Fig. 5(a), group 6 element 3 can be clearly resolved. This means that the achievable spatial resolution is about 6.2 µm. However, since the resolution test chart is an amplitude-only object, the reconstructed phase in the opaque region is severely contaminated by noise. Therefore, the spatial resolution of the phase image does not look good enough. In this case, we set the sampling ratio to 62.2%. The imaging acquisition time is about 334 minutes.

IV. CONCLUSION

In summary, we propose and experimentally demonstrate a novel complex-amplitude imaging method. By utilizing a phase-only SLM to generate coherent Fourier basis patterns as illumination, we can use a single-pixel detector to acquire the complex-valued Fourier spectrum of an object. In experiments, we implement this CFSI method with two etched glass objects, a damselfly wing, and a resolution test chart. The reconstructed complex-amplitude images have clear amplitude, accurate phase and spatial resolution of up to 6.2 µm. In addition, due to the use of common-path interference, the experimental configuration of this CFSI is compact and stable, which is readily integrated into commercial microscopes for quantitative phase microscopy. Thus, this complex-amplitude imaging method might find broad applications in optical metrology and biomedical science, especially for the cases with a light of invisible wavelength or extremely low intensity.

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DATA AVAILABILITY

Data underlying the results presented in this paper are available in Dataset (Ref. [36]).

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