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Image fidelity improvement in digital holographic microscopy using optical phase conjugation

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ABSTRACT

With respect to digital holography, techniques in suppressing noises derived from reference arm are maturely developed. However, techniques for the object counterpart are not being well developed. Optical phase conjugation technique was believed to be a promising method for this interest. A 0°-cut $BaTiO_3$ photorefractive crystal was involved in self-pumped phase conjugation scheme, and was employed to in-line digital holographic microscopy, in both transmission-type and reflection-type configuration. On pure physical compensation basis, results revealed that the image fidelity was improved substantially with 2.9096 times decrease in noise level and 3.5486 times increase in the ability to discriminate noise on average, by suppressing the scattering noise prior to recording stage.

1. Introduction

Digital holography (DH), wherein interference patterns are captured using charge-coupled devices (CCD), was pioneered by Schnars and Jüptner in 1994 [1]. They used numerical reconstruction of optical wavefronts to retrieve information of objects, which are fundamental to DH. DH has not only improved the image quality of a conventional microscopy with extended depth of focus, but also conferred considerable advantages over physical methods, particularly time saving (avoiding chemical developing procedures). With computational tools, both zero-order (DC) and first-order conjugate (twin image) noise term can be suppressed numerically, such as angular spectrum filtering [2], speckle method [3], and phase shifting [4–6] techniques. Nevertheless, these profound techniques only suppress noises that are derived from reference arm; the object arm, on the other hand, is not being paid with equivalent attention.

Noises contributed by hardware and electronics [7,8] are significant. Nevertheless, scattering due to optical elements, dust particles or even the object of interest itself is quite inevitable; if the object signal itself associates terrible noises, those noises will of course be reconstructed alongside with. In terms of suppressing scattering light, phase modulation [9], coherence modulation [10], polarization modulation [11,12], intensity modulation [13], frequency modulation [14] and correlation algorithms [15] are common techniques. However, additional optical elements are feasible but may also be potential sources of scattering noise; hence, these techniques can only suppress scattering noise to a certain extent. Notwithstanding, there is another candidate that had been active from 1980 to 2000, possess huge potential in suppressing scattering noise, i.e. phase conjugation technique. It is a unique technique that enables back propagation of wave to its original state. This property is perfect for suppressing scattering noise – in an ideal scenario, if a scattered signal is traced back to a point just before it scatters, no scattering noises will present in the signal.

There are of course many methods available in performing phase conjugation; in digital holographic microscopy (DHM), new phase conjugation technique has been reported, namely digital optical phase conjugation [16,17], was used to enhance the signal quality by suppressing turbidity of the object. Meanwhile, phase conjugation involving nonlinear optics has also been reported; however, the photorefractive crystals were used as a medium to record hologram [18,19], extracting conjugated wave from the negative first-order diffraction term. The photorefractive crystals were simply utilized for their dynamic properties of rewriting different holograms for different objects; however, writing and reading holograms (producing phase-conjugated wave) were performed separately. Nonetheless, these endeavors showed great improvement in the quality of reconstructed images by undoing scattering noise using phase conjugation techniques, prior to recoding stage. Thus, it should be clear that suppression of noises from the object arm prior to the recording stage plays a significant role.

With respect to phase conjugation using photorefractive crystals, four-wave mixing is commonly used [20]. With our empirical knowl-

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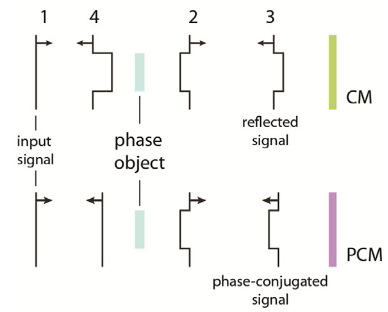

Fig. 1. Schematic of noise suppression using optical phase conjugation technique.

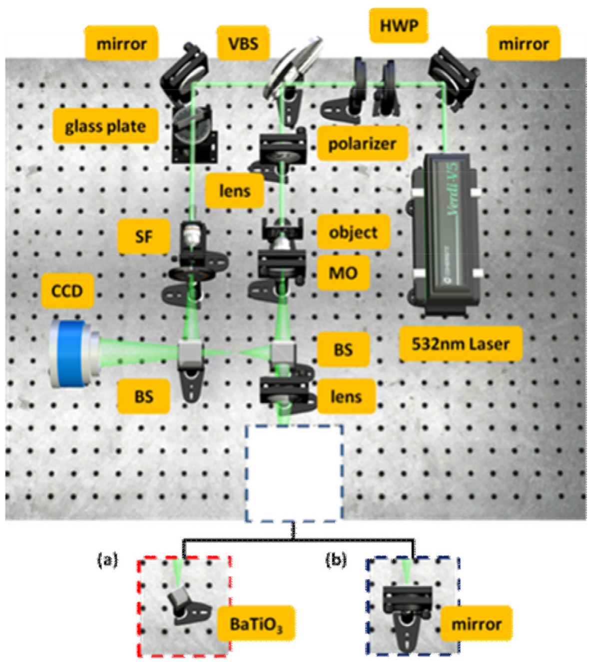

Fig. 2. Transmission-type SPPCDHM. Manipulated optical elements are delineated by dotted-line boxes: (a) a 0°-cut $BaTiO_3$ photorefractive crystal as PCM, and (b) control set with the use of CM.

edge upon optical phase conjugation (OPC) [21,22], we determined that OPC via photorefractive crystals suppresses scattering noise but intrinsically does not have a high spatial resolution and fails to compensate for relatively high spatial frequency signals due to its dimension. By contrast, microscopy enhances both the resolution and scattering. These two techniques appear to have a complementary relationship, and their combination can be optimized to obtain a favorable result. Furthermore, $BaTiO_3$ photorefractive crystal is one of the promising choices that inherit excellent coupling characteristics [23]. Thence, this paper presents a novel application that utilizes $BaTiO_3$ photorefractive crystal for self-pumped phase conjugation (SPPC) [24] in DHM (SPPCDHM) to suppress scattering noise prior to recording stage. Different from previous methods, the combinations of gratings formed within the photorefractive crystal are being simultaneously read and written, enabling near real time phase conjugation.

2. Theoretical background

2.1. Phase conjugation

In order to show that how phase conjugation technique suppresses scattering noises prior to recording stage, a qualitative illustration is shown in Fig. 1. A plane wave carried twice the phase delay introduced by the phase object using a conventional mirror (CM), whilst phase-conjugated mirror (PCM) on the other hand, showed that the reflected signal is retraced to its initial form. The illustration of course can be expended to arbitrary wavefront rather than just plane wave. Hence, by using a PCM, those double-passed elements were as if they did not exist; thus, noises were suppressed.

Since the return signal is phase conjugated, an inversion of sign with respect to phase distribution is expected. The return complex amplitude of that using CM and PCM is expressed in Eqs. (1) and (2), respectively, for the case of using phase shifting technique.

$$H'_{1,CM} - H'_{2,CM}\left(e^{-i\Delta\phi}\right) = \psi_O \psi_R^*\left(1 - e^{-i2\Delta\phi}\right), \tag{1}$$

$$H'_{1,PCM} - H'_{2,PCM}\left(e^{-i\Delta\phi}\right) = \psi_O^* \psi_R^*\left(1 - e^{-i2\Delta\phi}\right). \tag{2}$$

H'_1 and H'_2 are holograms before and after phase modulation respectively, which were subjected to zero-order noise suppression. ψ_O and ψ_R denotes the object wave and reference wave, whilst $\Delta\phi$ represents the phase modulation respectively. ψ_R is assumed to be a plane wave, and can be treated as a plane wave in our case [25]. The asterisk sign (*) denotes complex conjugate of the wavefront. Hence, it is possible to reconstruct images using only free space propagation to show intrinsic improvement in image fidelity.

2.2. Measure of image fidelity

2.2.1. Signal-to-noise-ratio

In order to show quantitative gain of the capacity of phase conjugation technique in suppressing noises, signal-to-noise ratio (SNR) of reconstructed images is evaluated. To calculate SNR, a reference signal is required. In terms of intensity, a reference signal can be easily obtained; however, the phase counterpart that requires numerical method would be less objective. Nevertheless, since DHM is very sensitive to phase perturbation, any suppression of noises would be distinctive even with qualitative comparison. Hence, the discussion of SNR will be limited to the aspect of intensity only. Let the image (without interference) recorded at the image plane to serve as the reference basis $A(x, y)$, while the same image of that subjected to externally added noise via a transparency will serve as the test image $B(x, y)$. Consider the recorded images have size of $M \times N$, the evaluation method for SNR can be expressed as

$$SNR_{A,B} = 10\log_{10}\left(\frac{\sum_{x=1}^{N}\sum_{y=1}^{M}|A(x,y)|^2}{\sum_{x=1}^{N}\sum_{y=1}^{M}|A(x,y) - B(x,y)|^2}\right). \tag{3}$$

The concept of SNR may be a bit vague in here. So, instead of decibels, the obtained figures are translated into weightage, W, which is of course equals to noise/(noise + signal). Noise is obtained from the denominator of SNR; likewise, signal is obtained from the numerator.

$$W = \frac{Noise}{Noise + Signal}. \tag{4}$$

2.2.2. Discrimination of noise

SNR provides us the noise level associated with the signal of interest. It is however that we have no confidence in differentiating noise and signal from one and the other. Thus, a new measuring criterion should be introduced. Since the added noise were mostly due to (but not limited to) scattering, which has lower intensity (true in general); thus, using intensity thresholding to discriminate (distinguish) signal and noise would be reasonable. The threshold value would then indicates that a signal is required to have intensity greater than the threshold value (relative to the max intensity), in order to be considered as signal, but not noise. Therefore, the higher the threshold value, one can discriminate noise from the signal of interest with greater confidence.