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Compressive optical image encryption with two-step-only quadrature phase-shifting digital holography

Jun Li*, Hongbing Li, Jiaosheng Li, Yangyang Pan, Rong Li

Laboratory of Quantum Engineering and Quantum Materials, School of Physics and Telecommunication Engineering, South China Normal University, Guangzhou 510006, China

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ABSTRACT

An image encryption method which combines two-step-only quadrature phase-shifting digital holography with compressive sensing (CS) has been proposed in the fully optical domain. An object image is firstly encrypted to two on-axis quadrature-phase holograms using the two random phase masks in the Mach–Zehnder interferometer. Then, the two encrypted images are highly compressed to a one-dimensional signal using the single-pixel compressive holographic imaging in the optical domain. At the receiving terminal, the two compressive encrypted holograms are exactly reconstructed from much less than the Nyquist sampling number of observations by solving an optimization problem, and the original image can be decrypted with only two reconstructed holograms and the correct keys. This method largely decreases holograms data volume for the current optical image encryption system, and it is also suitable for some special optical imaging cases such as different wavelengths imaging and weak light imaging. Numerical simulation is performed to demonstrate the feasibility and validity of this novel image encryption method.

1. Introduction

Information security has become an essential research subject and most security verification systems are based on images information. The study of image security includes image encryption, image watermarking and image hiding [1–3]. In recent years, various methods are proposed for image security in optical means [4–12]. We have also demonstrated the feasibility of image encryption with two-step-only quadrature phase-shifting digital holography [13,14]. These methods may be some effective solutions to the future implementation of all-optical systems [15].

However, the large volume of data required for storing or transmitting holograms has been a main limiting factor of optical image security. In recent years researchers have proposed many hologram compression schemes to solve this problem [16,17], however, their effectiveness is limited by the introduction of laser speckling noise [18], and the realization of hologram compression is typically performed using the electronic means [19]. The newly developed theory of compressive sensing (CS) [20,21] brings a novel technique to hologram compression in the optical domain [22–25]. It is built on the inherent sparsity of images and can recover the compressed images with desirable quality from much fewer compressed data. Recently, various image encryption methods based on compressive sensing are proposed. Deepan et al. [26] proposed the multiple-image encryption by space multiplexing based on compressive sensing and the double-random phase-encoding technique. Subsequently, Huang et al. [27] presented a parallel image encryption method based on compressive sensing. Afterwards, Zhou et al. [28] proposed a novel image compression–encryption hybrid algorithm based on key-controlled measurement matrix in compressive sensing. However, these methods actually relate to digital image encryption, completely optical schemes for image encryption based on CS have seldom been discussed.

This paper proposes a completely optical image encryption method combined two-step-only quadrature phase-shifting digital holography with CS. We firstly encrypt the optical image utilizing the two random phase masks in the Mach–Zehnder interferometer and interference the encrypted object light with the reference light to get two on-axis quadrature-phase holograms. Then, the two encrypted interference patterns are highly compressed to a one-dimensional signal using the single-pixel compressive holographic imaging. At the receiving terminal, the two encrypted holograms are exactly reconstructed from small amounts of data by certain signal recovery algorithms of the CS theory and the original image can be decrypted with two only reconstructed holograms and the correct keys. This method effectively combines the two-step-only phase-shifting technique with the CS

* Corresponding author. Fax: +86 39310066.
E-mail address: lijunc@126.com (J. Li).

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technology in a purely optical system, which not only makes full use of the parallel processing property of the light for image encryption, but also largely compresses the data amount of the encrypted holograms in the optical domain. Thus, it largely decreases the holograms data volume for the current optical image encryption system, and it is also suitable for some special optical imaging cases such as different wavelengths imaging and weak light imaging. Moreover, our method could overcome the shortage of the precision, the cost, the wavelengths and the resolution of the CS-based array imaging for the adoption of a single-pixel detector. Section 2 introduced the principles of our method and numerical simulations are described in Section 3.

2. Fundamental principles

2.1. Image encryption and compression

Fig.1 shows the optical setup for an image encryption method combined two-step-only quadrature phase-shifting digital holography with CS. Where a linearly polarized laser beam is expanded, collimated, and then divided into an object beam and a reference beam. Firstly, an object image is illuminated by the object beam, which is used for encryption, and then passes through two random phase masks R_1 and R_2 to encrypt image using double random phase encoding (DRPE) method [1]. On the other hand, the phase of the reference wave is controlled by a piezoelectric transducer mirror (PZT). Then the two waves overlap to form an interference pattern in the plane of a Digital Micro-mirror Device (DMD). With a DMD producing the measurement matrix ψ, we computer random linear measurements of the interferograms I_H and the measurement matrix ψ, and then obtain the compressed data using a photodiode. Finally we can acquire the compressed hologram images by a traditional communication channel and then reconstruct it via the specific signal recovery algorithms of CS theory, and the original object can be decrypted using inverse Fresnel-transformed with only two reconstructed holograms and the correct keys.

For simplification, the reference wave is expressed by $R\cdot\exp(j\cdot 0)$. The complex object filed $U(x, y)$ on the DMD plane can be written as

$$U(x,y) = FR_{Z2}\left\{FR_{Z1}\left\{U(x_0,y_0)\exp\left[i2\pi\cdot p(x_0,y_0)\right]\right\}\times \exp\left[i2\pi\cdot q(x_1,y_1)\right]\right\}, \quad (1)$$

where $U_0(x_0, y_0)$ is a complex object field in the plane R_1. The complex amplitude transmittances of R_1 and R_2 are $\exp\left[i2\pi\cdot p(x_0,y_0)\right]$ and $\exp\left[i2\pi\cdot q(x_1,y_1)\right]$ respectively, where $p(x_0, y_0)$ and $q(x_1, y_1)$ are two independent white noises uniformly distributed in [0, 1]. z_1 is the distance between planes R_1 and R_2, and z_2 is the distance between R_2 and DMD. Where FR_Z denotes Fresnel transform of distance z.

In the case of the two-step algorithm based on the traditional two-step quadrature phase-shifting holography [29,30], when we set the phases of the reference wave in the first and second exposure to 0 and $\pi/2$ respectively, the two on-axis quadrature-phase holograms I_{H1} and I_{H2} on the DMD plane are sampled sequentially and expressed as

$$I_{H1} = \left|R + U(x,y)\right|^2 = I_0(x,y) + 2\,\mathrm{Re}\,[U(x,y)]\cdot R, \quad (2)$$

$$\begin{aligned} I_{H2} &= \left|R\cdot\exp(i\cdot\pi/2) + U(x,y)\right|^2 \\ &= \left|jR + U(x,y)\right|^2 \\ &= I_0(x,y) + 2\mathrm{Im}[U(x,y)]\cdot R, \end{aligned} \quad (3)$$

where I_0 is the zero-order light given by

$$I_0(x,y) = R^2 + \left|U(x,y)\right|^2. \quad (4)$$

A DMD consists of millions of micro-mirrors, and works by controlling the reflection of each individual pixel on the display. When the hologram I_H is formed on the DMD plane, the mirrors on the DMD is in a certain pseudorandom condition according to the restricted isometry property (RIP) [31] in CS theory, with the help of pseudorandom number generator (RNG), randomly selected mirrors of the DMD are oriented in a direction towards the lens (a “1”), while the rest are oriented in a different direction (a “0”), then the light reflected by the mirrors in direction towards lens is summed at the photodiode to compute the measurement as its output voltage

$$Y(m) = \{y_{1m}, y_{2m}\} = \phi_m[I_{H1}, I_{H2}], \quad (5)$$

here ϕ_m is the m-th pseudo-random matrix on the DMD plane, $m = \{1, 2, \ldots M\}$. The pseudo-random number generator is

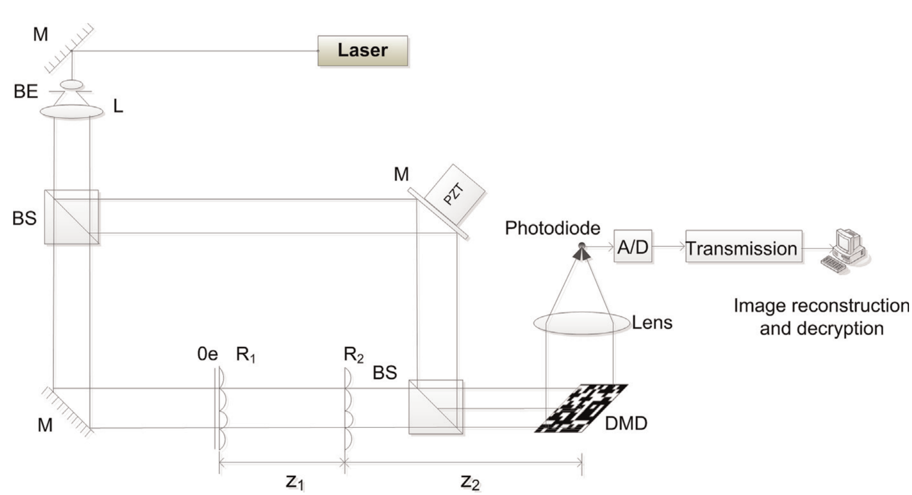

Fig. 1. The optical setup for an image encryption method combined two-step-only quadrature phase-shifting digital holography with CS. BE, beam expander; L, lens; BS, beam splitter; M, mirror; R, random phase plate; PZT, piezoelectric transducer mirror; Oe, object image.