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Pseudo color ghost coding imaging with pseudo thermal light

De-yang Duan *, Yun-jie Xia

College of Physical Engineering, Qufu Normal University, Qufu 273165, China
Shandong Provincial Key Laboratory of Laser Polarization and Information Technology, Research Institute of Laser, Qufu Normal University, Qufu 273165, China

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ABSTRACT

We present a new pseudo color imaging scheme named pseudo color ghost coding imaging based on ghost imaging but with multiwavelength source modulated by a spatial light modulator. Compared with conventional pseudo color imaging where there is no nondegenerate wavelength spatial correlations resulting in extra monochromatic images, the degenerate wavelength and nondegenerate wavelength spatial correlations between the idle beam and signal beam can be obtained simultaneously. This scheme can obtain more colorful image with higher quality than that in conventional pseudo color coding techniques. More importantly, a significant advantage of the scheme compared to the conventional pseudo color coding imaging techniques is the image with different colors can be obtained without changing the light source and spatial filter.

1. Introduction

Ghost imaging (GI) is a novel indirect imaging technique that acquires the image of an object through spatial intensity correlation measurements. Different from the conventional optical imaging, the object's image in GI setup is reconstructed by using two spatially correlated light beams: the idle beam, which never illuminates the object and is directly measured by a charge-coupled device(CCD), and the signal beam, which, after illuminating the object, is measured by a bucket detector. The "ghost" image is retrieved by measuring the cross correlation between the two photocurrents arising from the two detectors [1,2].

GI has become increasingly popular over the last decade, owing to its novel physical characteristics, e.g., atmospheric turbulence free [3–7]. These studies found that GI is a good candidate for imaging objects immersed in optically harsh environments [3,4,8,9]. Moreover, previous works show that GI has the capability of super resolution [10–12] indicating the potential applications in the field of biomedical imaging. Recently, the research of GI with X-ray source have been reported [13–15]. The GI has become a powerful tool in the exploring and analyzing the internal of complex material, e.g., biomolecular structures.

In practice, there are many black and white objects whose images' quality is not conducive for observation, e.g., the biological slices, X-ray film. As we all know, making these objects appearing as color images is a good way to improve its quality, as that obtained by GI [16]. However, this scheme cannot be substantially better than the conventional pseudo color coding imaging. In this article, we present a new pseudo color imaging scheme that can be substantially better than the previous schemes including not only conventional pseudo color coding imaging but also pseudo color coding imaging with GI.

In this article, we take the equal spatial frequency pseudo color coding and two-wavelength source as an example to illustrate the pseudo color ghost coding imaging. Then, we discuss the pseudo color ghost coding imaging with three-wavelength source. Finally, we discuss one salient advantage of the pseudo color ghost coding imaging, i.e., the images of different color can be obtained without changing the light source and spatial filter, which is impossible for conventional pseudo color coding imaging techniques.

2. Analysis

We take the pseudo color coding with equal spatial frequency as an example to illustrate the properties of the pseudo color ghost coding imaging (PCGCI). Certainly, this imaging scheme is also applicable to other pseudo color coding imaging techniques, e.g. equal density pseudo color coding [16]. In the setup depicted in Fig. 1, two continuous-wave lasers with center frequency ω_1 and ω_2 are coupled together by a dichroic mirror(DM) and pass through a SLM generating two light beams, that is, the signal beam and idle beam, by means of a 50:50 beam splitter(BS). The signal beam is used to illuminate the object, with the

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[*] Corresponding author.
E-mail addresses: duandy2015@qfnu.edu.cn (D.-y. Duan), yjxia@mail.qfnu.edu.cn (Y.-j. Xia).

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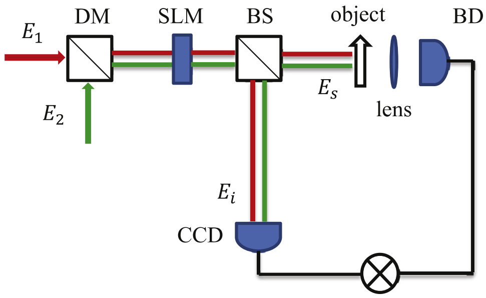

Fig. 1. Setup of the pseudo color ghost coding imaging with pseudo thermal light; SLM: spatial light modulator; DM: dichroic mirror; BS: beam splitter; BD: bucket detector. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

transmitted light being measured by a bucket detector. The idle beam is directly measured by a CCD camera. The object's image is retrieved by measuring the cross correlation between the two photocurrents arising from the two detectors.

In order to realize the pseudo color imaging, one lens is placed behind the object to implement the Fourier transformation depicted in Fig. 2. The signal beam illuminates a black-and-white object with complex amplitude $T(x, y)$. According to the Huygens–Fresnel principle, the complex amplitude on the focal plane of the lens can be expressed as

$$F(\zeta,\eta) = \iint_{-\infty}^{\infty} T(x,y) \exp\left[-i\frac{2\pi}{f\lambda}(\zeta x + \eta y)\right] dx dy, \tag{1}$$

and

$$F(u,v) = \iint_{-\infty}^{\infty} T(x,y) \exp\left[-i2\pi(ux+vy)\right] dx dy. \tag{2}$$

The quantities u, v represent the frequency domain coordinates of the ζ, η. The relationship is

$$u = \frac{\zeta}{f\lambda}, v = \frac{\eta}{f\lambda}. \tag{3}$$

The corresponding inverse Fourier transformation of Eq. (2) is

$$T(x,y) = \iint_{-\infty}^{\infty} F(u,v) \exp\left[i2\pi(ux+vy)\right] du dv, \tag{4}$$

where $T(x, y)$ is the spectral function of the spatial domain and $F(u, v)$ is the spectral function of the frequency domain. The complex amplitude $F(\zeta, \eta)$ over an L-m-long free-space path yields a new complex amplitude at the CCD plane(Fig. 2). Thus,

$$\begin{aligned} T(x',y') &= \iint_{-\infty}^{\infty} F(\zeta,\eta) \exp(ikr) d\zeta d\eta \\ &= \iint_{-\infty}^{\infty} F(\zeta,\eta) \exp\left[i\frac{2\pi}{\lambda}\sqrt{(x'-\zeta)^2+(y'-\eta)^2+l^2}\right] d\zeta d\eta \\ &\approx \iint_{-\infty}^{\infty} F(\zeta,\eta) \exp(ikl) \exp\left(ik\frac{x'^2+y'^2}{2l}\right) \\ &\quad \times \exp\left(ik\frac{\zeta^2+\eta^2}{2l}\right) \exp\left(-ik\frac{x'\zeta+y'\eta}{l}\right) d\zeta d\eta \\ &\approx \iint_{-\infty}^{\infty} F(\zeta,\eta) \exp(ikl) \exp\left(-ik\frac{x'\zeta+y'\eta}{l}\right) d\zeta d\eta \\ &= \iint_{-\infty}^{\infty} F(u,v) \exp(ikl) \left[-i\frac{2\pi f}{l}\left(xu'+yv'\right)\right] (f\lambda)^2 du dv \\ &= (f\lambda)^2 \iint_{-\infty}^{\infty} F(u,v) \exp(ikl) \exp\left[i2\pi(xu+yv)\right] du dv. \end{aligned} \tag{5}$$

In the calculation of Eq. (5), we assume $l \gg \sqrt{\zeta_{\max}^2 + \eta_{\max}^2}$ and $l \gg \sqrt{x'^2_{\max} + y'^2_{\max}}$. Compare Eq. (1) and Eq. (5), we have

$$T\left(x',y'\right) = (f\lambda)^2 \exp(ikl) T(x,y). \tag{6}$$

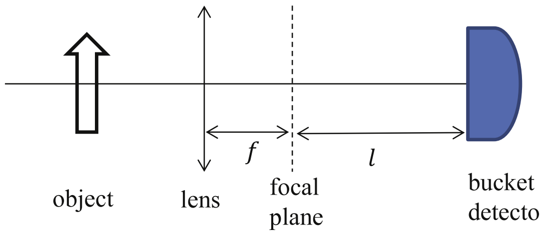

Fig. 2. The schematic of the Fourier transformation.

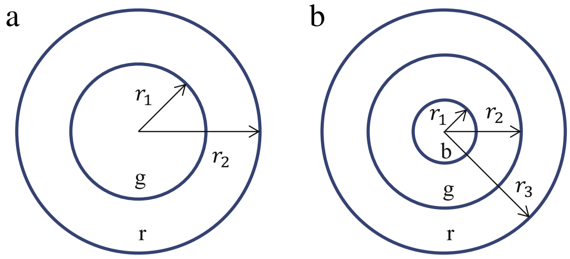

Fig. 3. The schematic of the spatial filter. r: red; g: green; b: blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Eq. (6) reveals that the complex amplitude at the bucket detector plane is the same as that of the object. Consequently, the quantity, $T\left(x', y'\right)$, changes with the variety of the wavelength.

Since the spatial filtering is an effective method to realize pseudo color imaging, we would therefore adopt a two-dimensional spatial filter for pseudo color ghost coding imaging scheme as shown in Fig. 3(a). For simplicity, this filter divides the spatial frequency into two regions, each of which allows one wavelength light pass through, i.e., the green light can pass through when $r < r_1$, and the red light can pass through when $r_1 < r < r_2$. The complex amplitude transmission function of the filter can be expressed as

$$h(\lambda_m) = \begin{cases} h(\lambda_g) \\ h(\lambda_r) \end{cases}, \tag{7}$$

where $m = g, r$, g and r represent the green and red light.

The light field of the idle beam detected by the CCD and that of the signal beam detected by the bucket detector can be expressed as

$$E_i(\vec{\rho}_i,t) = E_{ig}(\vec{\rho}_i,t) + E_{ir}(\vec{\rho}_i,t) \tag{8}$$

$$E_s(\vec{\rho}_i,t) = E_{sg}(\vec{\rho}_i,t) + E_{sr}(\vec{\rho}_i,t), \tag{9}$$

where

$$E_{im}(\vec{\rho}_i,t) = \int d\omega d\vec{q} e^{-i\omega t} V(\vec{q}) \varepsilon_i(\omega) H_i(\vec{\rho}_i,\vec{q};t), \tag{10}$$

$$E_{sm}(\vec{\rho}_s,t) = \int d\omega d\vec{q} e^{-i\omega t} V(\vec{q}) \varepsilon_s(\omega) H_s(\vec{\rho}_s,\vec{q};t) T\left(\rho'\right). \tag{11}$$

Here, the light fields incident on the SLM are taken to be plane wave with spectra $\varepsilon(\omega)$. The SLM produces spatial amplitude modulation of the light fields represented by the function random spatial mask function $V(\vec{q})$, which is taken to the same for light with different wavelengths [17]. The functions H_i and H_s are Huygens–Fresnel Green's functions [2,17,18] that describe propagation of the signal and idle beams. The quantities $\vec{q}$ and ρ represent wave vector and transverse position.

The ghost image is reconstructed by measuring the cross correlation between the outputs of the bucket detector and CCD [1,19,20]. So we obtain

$$C(\vec{\rho}_i,\vec{\rho}_s,t) = \left\langle \delta I_i(\vec{\rho}_i,t) \delta I_s(\vec{\rho}_s,t) \right\rangle, \tag{12}$$