Optics Communications 410 (2018) 867–870

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Robust reflective ghost imaging against different partially polarized thermal light

Hong-Guo Li [a], Yan Wang [a], Rui-Xue Zhang [a], De-Jian Zhang [b], Hong-Chao Liu [c], Zong-Guo Li [a,*], Jun Xiong [d]

[a] School of Science, Tianjin University of Technology, Tianjin 300384, China
[b] Department of Physics, Nanchang University, Nanchang 330031, China
[c] School of Physics and Astronomy, University of Birmingham, Birmingham B152TT, United Kingdom
[d] Department of Physics, Applied Optics Beijing Area Major Laboratory, Beijing Normal University, Beijing 100875, China

ARTICLE INFO

Keywords:
Reflective ghost imaging
Degree of polarization
Contrast-to-noise ratio

ABSTRACT

We theoretically study the influence of degree of polarization (DOP) of thermal light on the contrast-to-noise ratio (CNR) of the reflective ghost imaging (RGI), which is a novel and indirect imaging modality. An expression for the CNR of RGI with partially polarized thermal light is carefully derived, which suggests a weak dependence of CNR on the DOP, especially when the ratio of the object size to the speckle size of thermal light has a large value. Different from conventional imaging approaches, our work reveals that RGI is much more robust against the DOP of the light source, which thereby has advantages in practical applications, such as remote sensing.

1. Introduction

Ghost imaging (GI) is an indirect imaging technique that acquires the image of an object by means of spatial intensity correlation measurements. The source beam is divided into two spatially correlated beams, one beam passing through an object and detected by a bucket detector, while the other not interacting with the object measured by a spatially resolving detector. The object image can be reconstructed by correlating the output signals from these two detectors. Shih's group first realized GI with an entangled light source in 1995 [1]. It was subsequently proved that GI can also be achieved with classical sources i.e. pseudo-thermal or true thermal light [2–10]. In addition, computational ghost imaging (CGI) was presented theoretically by Shapiro et al. [11] and performed experimentally by Bromberg et al. [12]. Later, some methods are applied to improve the image quality of CGI, such as compressive GI [13], single pixel imaging [14,15] et al. Since a programmable light source can be used, CGI is more convenient for potential applications.

In general, the image quality can be evaluated by visibility, resolution or contrast-to-noise ratio (CNR) [16–18]. The influences of the transverse coherence length, the object size, and detector response speed etc. on the image quality of transmissive ghost imaging have been discussed in previous studies [19–25]. In terms of second-order coherence theory, Cai et al. [8] demonstrated that the quality of ghost image with partially coherent light (pseudothermal light) is related to the coherence properties of the light source. Most these studies on ghost imaging are based on the classical optical coherence theory, ignoring the vector nature of light.

In ghost imaging scheme, the random speckle patterns of thermal light source, which function as illumination, are essentially related to the coherence properties of the source and consequently to the polarization of the light. Accordingly, Liu et al. [26,27] and Kellock et al. [21] recently discussed the role of degree of polarization (DOP) in transmissive ghost imaging, which only focused on the high-order transmissive GI case and ignored the ratio of the object size to the speckle size of light source.

Recently, many studies demonstrate that the reflective ghost imaging (RGI) can be applied and more feasible in remote sensing or laser radar [28–32]. Considering the fact that James [33] found that when the light is partially coherent, the DOP will vary as the beam propagates even in free space, the DOP of the light will change after a long-distance propagation and consequently maybe influences the image quality of ghost imaging in remote sensing.

Thus, in this paper, we will investigate the effect of DOP on the CNR of RGI according to the probability density function of partially polarized thermal light. By taking the ratio of the object size to the speckle size of light source into consideration, we carefully derive an

* Corresponding author.
E-mail address: zgli@tjut.edu.cn (Z.-G. Li).

https://doi.org/10.1016/j.optcom.2017.11.061
Received 19 September 2017; Received in revised form 6 November 2017; Accepted 21 November 2017
0030-4018/

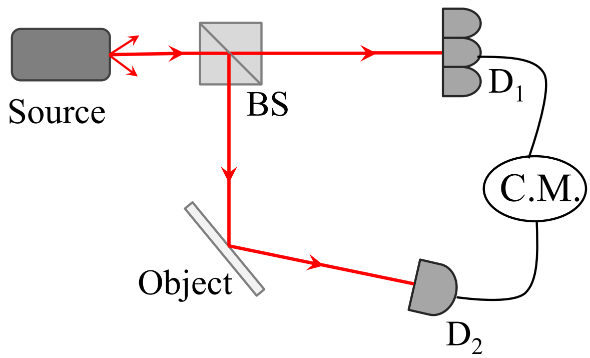

Fig. 1. The scheme of RGI with thermal light. Source: thermal light source; BS: beam splitter; D_1: spatially resolving detector; D_2: bucket detector; Object: reflective object; C.M.: correlation measurement.

expression for the CNR of RGI with partially polarized thermal light, which indicates a weak dependence of CNR on the DOP. When the ratio of the object size to the speckle size of light source takes a large value (i.e., a most general case in practical application of GI), the influence of DOP on the CNR can be ignored. Our work manifests that a robust CNR can be expected in RGI with different partially polarized light, which therefore has merits in practical applications, such as long-distance imaging in which case the scattering and the atmosphere turbulence are unavoidable and the DOP of light is difficult to maintain. The paper is organized as follows. In Section 2, we derive an expression for the CNR of RGI and then theoretically discuss how the DOP of thermal light affects the CNR of RGI. In Section 3, the conclusion is made.

2. Theoretical analysis

The scheme of RGI is shown in Fig. 1. Thermal light is split by a beam splitter and propagates through paths 1 and 2 to detectors D_1 and D_2, respectively. In path 1, the light that does not interact with the object is detected by a spatially resolving detector D_1. In path 2, the light interacts with the reflective object and is collected by a bucket detector D_2. The image of the object can be reconstructed by measuring the intensity fluctuation correlation between these two detectors.

In this paper, we assume that the illuminating light is sufficiently intense. We will follow the assumptions from Zerom et al. [23] in studying the influence of DOP on the CNR of RGI. Zerom et al. [23] presented a successful analysis of thermal ghost imaging quality according to the statistical properties of thermal light with three simplified but reasonable assumptions: (1) the intensities of illuminating speckle patterns are statistically independent from each other, (2) the intensities at each pixel are uncorrelated with the intensity at each other pixel, and (3) the measured signal variation of the detector mainly comes from the random intensity fluctuation of the incident speckle fields so that other noise sources (e.g., detector dark noise) can be ignored [34].

Accordingly, the second-order correlation function of RGI with thermal light can be expressed as [23]

$$G(\vec{x}) = \frac{1}{K}\sum_{k=1}^{K} I_o^{(k)} I^{(k)}(\vec{x}) - \frac{1}{K^2}\sum_{k=1}^{K} I_o^{(k)} \sum_{k=1}^{K} I^{(k)}(\vec{x}), \tag{1}$$

where

$$I_o^{(k)} = \sum_{\vec{x}} I^{(k)}(\vec{x}) O(\vec{x}), \tag{2}$$

is the total intensity of reflected light measured by the bucket detector for the kth measurement, $I^{(k)}(\vec{x})$ is the intensity distribution measured by the spatially resolving detector for the kth measurement at location $\vec{x}$, K denotes the total number of measurements, and $O(\vec{x})$ is the reflectivity function of the object. For simplicity, we here assume that the object is a binary (black-and-white) reflective object and the reflectivity function is

$$O(\vec{x}) = \begin{cases} R_1 & \text{white area,} \\ R_2 & \text{black area.} \end{cases} \tag{3}$$

For a reflective object with binary reflectivity, the CNR of ghost image, which is the ratio of background-subtracted correlation to its noise, can be defined as [18,23]:

$$CNR = \frac{\langle G(\vec{x}_{R_1})\rangle - \langle G(\vec{x}_{R_2})\rangle}{\sqrt{\Delta^2 G(\vec{x}_{R_1}) + \Delta^2 G(\vec{x}_{R_2})}}, \tag{4}$$

where $\vec{x}_{R_1}$ and $\vec{x}_{R_2}$ correspond to the pixels in the white area and black area of the object, respectively, $\langle \cdots \rangle$ denotes the ensemble average and $\Delta^2 G = \langle G^2\rangle - \langle G\rangle^2$ is the variance of the second-order correlation function. In terms of the first assumption, the expressions for the expected imaging signal of RGI and the corresponding variance are the same as those for transmissive ghost imaging [23]. These two expressions can be expressed as, respectively,

$$\langle G(\vec{x})\rangle = \frac{K-1}{K}[\langle I_o I(\vec{x})\rangle - \langle I_o\rangle\langle I(\vec{x})\rangle], \tag{5}$$

and

$$\begin{aligned} \Delta^2 G(\vec{x}) = & \frac{(K-1)^2}{K^3}\langle I_o^2 I^2(\vec{x})\rangle \\ & + \frac{(K-1)(K-2)}{K^3}\left[\langle I_o\rangle^2\langle I^2(\vec{x})\rangle + \langle I_o^2\rangle\langle I(\vec{x})\rangle^2 - \langle I_o I(\vec{x})\rangle^2\right] \\ & + \frac{K-1}{K^3}\langle I_o^2\rangle\langle I^2(\vec{x})\rangle + \frac{2(K-1)(3K-4)}{K^3}\langle I_o I(\vec{x})\rangle\langle I_o\rangle\langle I(\vec{x})\rangle \\ & - \frac{2(K-1)(2K-3)}{K^3}\langle I_o\rangle^2\langle I(\vec{x})\rangle^2 \\ & - \frac{2(K-1)^2}{K^3}\left[\langle I_o I^2(\vec{x})\rangle\langle I_o\rangle + \langle I(\vec{x}) I_o^2\rangle\langle I(\vec{x})\rangle\right]. \end{aligned} \tag{6}$$

We then define $\langle I^m(\vec{x})\rangle \equiv \mu_m$, which is the mth moment of intensity distribution of illuminating speckle pattern. According to the second assumption, after some calculations we arrive at the following relations

$$\langle I(\vec{x})\rangle = \mu_1, \tag{7}$$

$$\langle I_o\rangle = (M_1 R_1 + M_2 R_2)\mu_1, \tag{8}$$

$$\langle I^2(\vec{x})\rangle = \mu_2, \tag{9}$$

$$\begin{aligned} \langle I_o^2\rangle = & (M_1 R_1^2 + M_2 R_2^2)\mu_2 + [M_1(M_1-1)R_1^2 \\ & + M_2(M_2-1)R_2^2 + 2R_1R_2M_1M_2]\mu_1^2, \end{aligned} \tag{10}$$

$$\langle I(\vec{x}) I_o\rangle = O(\vec{x})\mu_2 + \left[M_1R_1 + M_2R_2 - O(\vec{x})\right]\mu_1^2, \tag{11}$$

$$\langle I^2(\vec{x}) I_o\rangle = O(\vec{x})\mu_3 + \left[M_1R_1 + M_2R_2 - O(\vec{x})\right]\mu_2\mu_1, \tag{12}$$

$$\begin{aligned} \langle I(\vec{x}) I_o^2\rangle = & O^2(\vec{x})\mu_3 + [2(M_1R_1 + M_2R_2)O(\vec{x}) \\ & + M_1R_1^2 + M_2R_2^2 - 3O^2(\vec{x})]\mu_2\mu_1 \\ & + [M_1(M_1-1)R_1^2 + M_2(M_2-1)R_2^2 \\ & + 2R_1R_2M_1M_2 - 2(M_1R_1 + M_2R_2)O(\vec{x}) \\ & + 2O^2(\vec{x})]\mu_1^3, \end{aligned} \tag{13}$$

$$\begin{aligned} \langle I^2(\vec{x}) I_o^2\rangle = & O^2(\vec{x})\mu_4 + [2(M_1R_1 + M_2R_2)O(\vec{x}) - 2O^2(\vec{x})]\mu_3\mu_1 \\ & + [M_1R_1^2 + M_2R_2^2 - O^2(\vec{x})]\mu_2^2 \\ & + [M_1(M_1-1)R_1^2 + M_2(M_2-1)R_2^2 + 2R_1R_2M_1M_2 \\ & - 2(M_1R_1 + M_2R_2)O(\vec{x}) \\ & + 2O^2(\vec{x})]\mu_2\mu_1^2, \end{aligned} \tag{14}$$

where M_1 and M_2 are defined as the ratios of the white area and black area of the object to the speckle size, respectively. Substituting