A novel correlation imaging method using a periodic light source array

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ABSTRACT

We propose and demonstrate a new correlation imaging method using a periodic light source array. The image of the object is reconstructed by exploiting the correlation between the total intensity of the beam interacting with the object and the precomputed intensity distribution patterns of the light source. The implementation of this experiment is quite simple and low-cost without the need for a beam splitter or spatial light modulator. Due to its single-pixel detection configuration, it should have great potential in many imaging applications.

Keywords: Correlation imaging, ghost imaging, computational imaging, image reconstruction techniques.

1. INTRODUCTION

Ghost imaging (GI), a nonlocal imaging method whereby an object is reconstructed by means of intensity correlation between the object beam and a corresponding reference beam, has attracted considerable attention in recent years. The setup is fairly simple, using a bucket detector (a single-pixel detector which has no spatial resolution) to measure the intensity of the beam interacting with the object, while a high-resolution planar detector is placed in the unobstructed reference beam. The image of the object is then reconstructed by exploiting the correlation between the two light beams. Later, computational GI was proposed by Shapiro [1], in which the need for a beam splitter is eliminated by using a spatial light modulator (SLM) capable of creating deterministic speckle patterns to illuminate the object [2, 3]. This system is more practical and suitable for remote sensing since the high resolution detector in the reference beam is replaced by a computer generated propagating field. In GI a ghost image of the object is retrieved by correlating the object beam with the reference beam, but in computational GI the measurements recorded by the bucket (single-pixel) detector in the object beam are convoluted with the precomputed intensity distribution patterns.

The first GI experiment, based on the quantum nature of the signal and idler photon pairs produced in spontaneous parametric down-conversion, was demonstrated by Pittman et al. in 1995 [4]. In their experiment, the signal and idler beams were separated from each other by a polarization beam splitter. An aperture mask and an imaging lens were placed in the object arm of the optical setup just before a bucket detector, while there was no optical element in the reference arm. However, the image of the aperture was obtained in the coincidence counts by scanning the reference detector in the plane defined by a two-photon Gaussian thin lens equation, even though the single counting rates of both detectors were fairly constant during the scanning. This phenomenon was named ghost imaging due to the fact that the image of the object is formed by photons that never actually pass through the aperture, and at first it was believed that quantum entanglement is a

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prerequisite for GI [5, 7]. Later, correlated imaging was realized by using a classical thermal light source [8], pseudothermal light generated by a laser beam passing through a rotating ground glass plate [9, 10], true thermal light from a hollow cathode lamp [11], and even sunlight [12].

Here, we propose and demonstrate a new correlated imaging method using a periodic light source array which itself can be directly modulated, so that there is no need for any SLM. The source is an array composed of M×N sub-sources, modulated by a control card to generate binary illumination patterns, which are projected onto an object while a bucket detector is placed at the other side to collect the total intensity of the transmitted light. The image of the object is retrieved by correlating the precomputed intensity distribution patterns of the source and the total intensities measured by the bucket detector. The periodic source used in our experiment is a light-emitting diode (LED) array consisting of 64×32 units. A sharp image of the double-slit is obtained by second-order correlation with only 1000 measurements. In the implementation of our method, neither complex arithmetic nor expensive equipment is required since both the beam splitter and the SLM are no longer required.

2. CORRELATION IMAGING THEORY

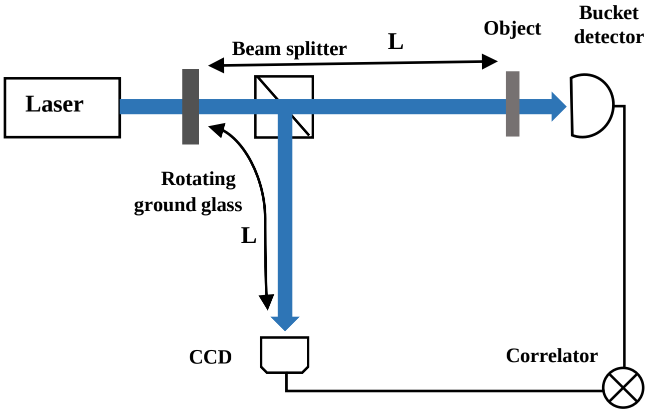

Fig. 1. Scheme for conventional GI.

In conventional GI with pseudothermal light, a laser beam passes through a rotating ground glass diffuser to produce a spatially random field $E(x_0)$, which is divided by a 50:50 beam splitter to produce identical object and reference beams, as shown in Fig. 1. At distance L from the rotating glass plate, the object beam illuminates a transmissive object, and the total transmitted field $E_1(x_1)$ at the bucket detector is given by Eq. 1. The CCD array is also at a distance L to detect the reference field $E_2(x_2)$ derived from the Huygens–Fresnel integral, as shown in Eq. 2 [13, 14].

$$E_1(x_1)=\frac{1}{\sqrt{\lambda L}}\int dx_0 E(x_0)\exp[-i\frac{\pi}{4}+ikL+\frac{ik}{2L}(x_1-x_0)]\mathrm{T}(x_1)\,, \tag{1}$$

$$E_2(x_2)=\frac{1}{\sqrt{\lambda L}}\int dx_0 E(x_0)\exp[-i\frac{\pi}{4}+ikL+\frac{ik}{2L}(x_2-x_0)]\,, \tag{2}$$

where x_0, x_1, and x_2 are the transverse coordinates on the glass plate, object plane and CCD detector plane, respectively, λ is the wavelength of the source, k its wavenumber, and $\mathrm{T}(x_1)$ the transmission function of the object. The second-order correlation function between the object and reference beams is given by Eq. 3. Information about the object is contained in the variance term $\Delta G(x_1, x_2)$ of Eqs. 3 and 4, in which the transmission function of the object can be retrieved by iterative correlation algorithms [10, 15, 16, 17, 18]:

$$\begin{aligned} G(x_1, x_2) &= \left\langle E(x_1)E(x_2)E^*(x_2)E^*(x_1)\right\rangle \\ &= \left\langle E(x_1)E^*(x_1)\right\rangle\left\langle E(x_2)E^*(x_2)\right\rangle + \Delta G(x_1, x_2) \end{aligned}, \tag{3}$$

where $\langle\,\rangle$ denotes an ensemble average over N measurements. We therefore find that

$$\Delta G(x_1, x_2) \propto \left|\mathrm{T}(x)\right|^2. \tag{4}$$

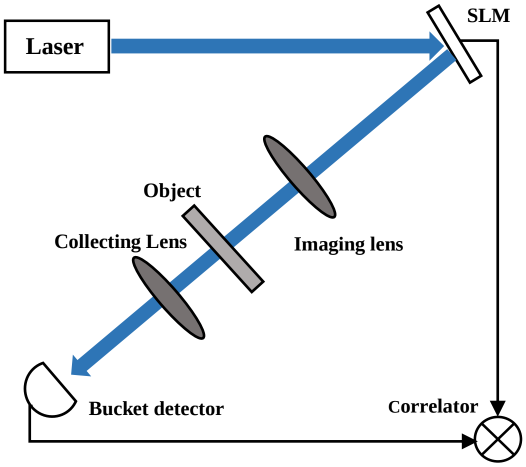

Fig. 2. Scheme for computational GI.

In the scheme of computational GI, as shown in Fig. 2, an SLM is used to control the intensity and/or phase of the incident light (laser beam), allowing the intensity structure to be calculated at any plane and stored in computer memory rather than having to be measured by a high-spatial resolution reference detector. The need for a beam splitter and rotating ground glass plate is also removed due to our prior knowledge of the modulation algorithm. The object information is retrieved by correlated measurements of the total intensity at the bucket detector and the time-varying speckle patterns on the SLM.

In our experiment, as shown in Fig. 3, the light source is a periodic array composed of M×N sub-sources, modulated directly by a control card to generate time-varying binary speckle patterns. The source and object are located at the object and image planes of a thin lens f_1, respectively. The total intensity S_i measured by the bucket detector with a collecting lens f_2 for the *i*-th measurement is:

$$S_i = \int dxdy I_i\left(x, y\right) T\left(x, y\right), \tag{5}$$

where $T\left(x, y\right)$ is the transmission function of the object which has spatial coordinates *x* and *y*, and $I_i\left(x, y\right)$ is the intensity of the illuminating field during the *i*-th measurement. After *N* measurements, the image of the object is retrieved by the second-order correlation function:

$$G(x,y)=\frac{1}{N}\sum_{i=1}^{N}\left(S_i-\langle S\rangle\right)I_i(x,y)=\left\langle SI(x,y)\right\rangle-\langle S\rangle\left\langle I(x,y)\right\rangle. \tag{6}$$

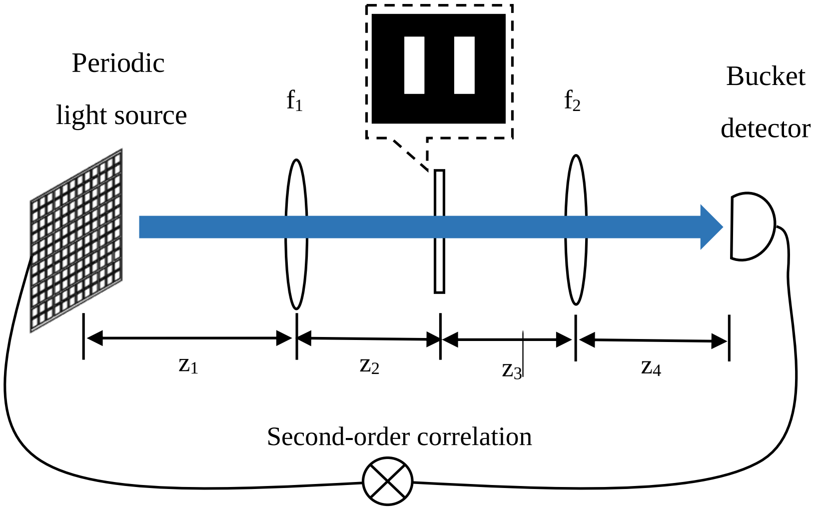

Fig. 3. Schematic of the experimental setup.

3. EXPERIMENTAL SETUP AND RESULTS

The schematic of our setup is shown in Fig. 3. The periodic light source is an array of 64×32 LEDs, where the center-to-center distance between adjacent diodes is 4.75 mm. Each LED, made from gallium arsenide phosphide with an emission wavelength between 650 to 700 nm, can be considered to be a circular unit of diameter 3.75 mm and can be individually controlled to display random binary on/off patterns generated by a computer.

The composite beam from the source passes through a thin lens of focal length f_1 = 35 mm through to the object, and then is collected by another thin lens of focal length f_2 = 2.5 mm. The distances shown in Fig. 1, z_1=1150 mm, z_2=157mm, and the focal length of the lens f_1 satisfy the Gaussian thin lens equation:

$$\frac{1}{z_1}+\frac{1}{z_2}=\frac{1}{f_1}\ . \tag{7}$$

The object used here is a double-slit, with a slit width of 5 mm, height 15 mm, and slit-distance 5 mm. The f_2 = 2.5 mm lens collects the transmitted light from the object plane after a distance of z_3=33.2 mm and focusses it into the bucket detector at a distance of z_4 = 2.5 mm. For convenience, the bucket detector used here is a charge-coupled device (CCD) camera, but it could be replaced by a photodiode or single-pixel detector.

The object's image is recovered from the second-order correlation function between the bucket detector and the illuminating intensity patterns, as given by Eq. 6.

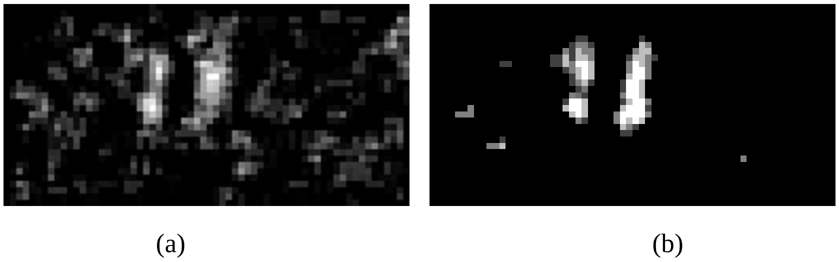
(a) (b)

Fig. 4. Second-order correlation image of the double slit after averaging over N exposures, for (a) N=500, (b) N=1000.

In our experiment, the exposure time for each iteration was 10 ms, and the image was reconstructed after a total number of N iterations. The retrieved image of size 64×32 pixels is shown in Fig. 4 (b), where N was only 1000, which is much less than the usual several thousands required for traditional GI. Although there is some noise present, the double-slit is clearly recognizable. The signal-to-noise ratio can be improved if the number of iterations is increased, as can be seen from Fig. 4, in which Fig. 4(a) is retrieved from only 500 measurements. The results could also be modified and improved with some conventional image processing programs.

4. CONCLUSION

In conclusion, we have performed the first experimental demonstration of computational GI using an LED array as a periodic light source, showing that correlated imaging can be realized with a periodic light array as the source of illumination. A 64×32 pixel image of the double-slit is obtained by second-order correlation with only 1000 measurements. The implementation is quite simple and low-cost since there is no need for a beam splitter or SLM, though the source is directly modulated. Furthermore, since the detector can be just a single-pixel diode, this method should have great potential in microscopy and medical imaging applications.

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