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Effects of light intensity on reflective ghost imaging

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Received February 11, 2014; accepted April 20, 2014; posted online June 20, 2014

In this letter, we analyze the effects of light intensity on reflective ghost imaging with thermal source. We find that the brightness of reflective ghost image can be changed by modulating the light intensity of the source and the splitting ratio of the beam splitter. The signal-to-noise ratio will be improved by increasing the light intensity of the source. More important, we can obtain the reflective ghost image with high image quality by adopting a low light intensity signal beam and a high light intensity reference beam, which is better than the classical optical imaging, because it can reduce the effects of light on the object.

OCIS codes: 270.3290, 030.6600.
doi: 10.3788/COL201412.072701.

Ghost imaging is a procedure for forming the image of an object indirectly, by means of correlation between two light beams to image an object without spatially resolving measurements of the light beam that has undergone object interaction. Ghost imaging is so-called because the photons that provide the spatial information regarding the object have never directly interacted with the object to be imaged. Recent work shows that the ghost imaging has significant meanings in understanding the quantum correlations. So the ghost imaging may be applied in the quantum information in the future.

An important reason of concerning about the ghost imaging over the last decade is its potential applications in many areas. For example, biomedical imaging and optical encryption. In the previous works, many factors affecting the image quality of ghost imaging, such as the source, lens, and atmospheric turbulence, were theoretically and experimentally analyzed in transmission-type ghost imaging system. Yet remote sensing applications require that the objects can be imaged in reflection. Recently, many works have also demonstrated the feasibility of reflective ghost imaging. In this letter, we analyze the effects of light intensity on reflective ghost imaging with thermal source in brightness, image contrast, and signal-to-noise ratio (SNR). Certainly, the transmission case can also be obtained based on our analysis.

We consider the reflective ghost imaging configuration in Fig.1. A laser beam passes through a rotating ground-glass (RG) to produce spatially incoherent signal and reference beams whose temporal bandwidths are much lower than those of the bucket detector and high spatial-resolution detector (charge-coupled device (CCD) array). The signal beam interacts with the object, but the reference beam does not interact with the object. Cross correlating the currents from the two detectors yields the ghost image, whose physical origin lies in the perfect correlation between the spatial fluctuations imposed by the source plane on the signal and reference beams.

Two optical beams generated by a laser beam, a signal field $\hat{E}_S(\rho, t)e^{-i\omega_0 t}$ and a reference field $\hat{E}_R(\rho, t)e^{-i\omega_0 t}$, that are scalar, positive-frequency, paraxial field operators normalized to have units $\sqrt{\text{photons/m}^2\text{s}}$. The quantities $\rho$ and $\omega_0$ are the transverse coordinate and center frequency, respectively. The commutation relations for the base-band field operators are given by

$$[\hat{E}_m(\rho_1, t_1), \hat{E}_l(\rho_2, t_2)] = 0,$$

$$[\hat{E}_m(\rho_1, t_1), \hat{E}_l^\dagger(\rho_2, t_2)] = \delta_{m,l} \delta(\rho_1 - \rho_2)\delta(t_1 - t_2),$$

where $m, l = 1, 2$, $\delta_{ml}$ is the Kronecker delta, and $\delta(\cdot)$ is the unit impulse.

The currents from the bucket detector and each pixel on the CCD are sent to a correlator with coincidence measurement, whose output for the CCD pixel located at transverse coordinate $\rho_1$ is given by

$$\hat{C}(\rho_1) = \frac{1}{T_1} \int_{-T_1/2}^{T_1/2} dt_1 i_1(t_1)i_2(t),$$

where $T_1$ is the average time and we have suppressed an $L/c$ time delay in $i_1(t)$ that is need to account for the

![Fig. 1. Setup of the reflective ghost imaging.](Image)
delay incurred by the reflective light from the object. We consider two ideal detectors that are assumed to have identical subunity quantum efficiencies and finite electrical bandwidths with no dark current or thermal noise contributing to the output current. The output currents corresponding to the following quantum measurements are given by\cite{20,22}

\[ i_m(t) = q \int d\tau \int_{A_m} d\rho \, \hat{E}_{m,\tau}^\dagger(\rho, \tau) \hat{E}_{m,\tau}(\rho, \tau) \rho_B(t - \tau), \]  

(4)

where \( A_1 \) and \( A_2 \) denote the area of one pixel in the reference arm and the photosensitive surface of the bucket detector; \( q \) is the electron charge; \( \rho_B(t) \) is a real impulse response to model the real detector's finite electrical bandwidth.

\[ \hat{E}_{m,\tau}(\rho, t) \equiv \sqrt{\eta} \hat{E}_m(\rho, t) + \sqrt{1 - \eta} \hat{E}_{vac,\tau}(\rho, t), \]

\[ m = 1, \]

(5)

\[ \sqrt{\eta} \] is the detector's quantum efficiency, and \( \hat{E}_{vac,\tau}(\rho, t) \) is a Vacuum-state field operator. The function \( \hat{E}_{m,\tau}(\rho, t) \) represents the light field detected by the bucket detector.

\[ \hat{E}_1(\rho, t) = \int d\rho' \hat{E}_1(\rho', t) h_1(\rho' - \rho), \]

(6)

\[ \hat{E}_2(\rho, t) = \int d\rho' \hat{E}_2(\rho', t) h_1(\rho' - \rho), \]

(7)

\[ \hat{E}'_2(\rho, t) = \int d\rho'' \hat{E}_2(\rho'', t) h_1(\rho'' - \rho), \]

(8)

where \( h_1(\rho) \) is the Huygens-Fresnel-Green's function:

\[ h_1(\rho) = \frac{k_0 e^{i k_0 (L + \frac{\rho^2}{2\pi})}}{2i\pi L}, \]

(9)

\( k_0 = \omega_0/c \) is the wave number associated with the center frequency, \( T(\rho) \) is the object's field-reflection coefficient. We have neglected time delays.

Because the objects for reflective ghost imaging will have microscopic surface variations from a nominal, smooth surface profile—whose standard deviations can greatly exceed the illumination wavelength and whose transverse correlation scale can be sub-wavelength. If this object is illuminated by laser, it gives rise to laser speckle in the reflective signal beam. Therefore, we will use a reasonable statistical model for \( T(\rho) \)\cite{6,30},

\[ \langle T(\rho_1) T(\rho_2) \rangle = \lambda_0^2 T(\rho_1) \delta(\rho_1 - \rho_2), \]

(10)

where \( \lambda_0 \) is the center wavelength of the illumination light, and we will omit it in the following calculation. \( T(\rho_1) \) is physically the mean square speckle reflection coefficient at location \( \rho_1 \), and at the same time, it represents the object information that is sought.

\[ \hat{C}(\rho_1) \] measurement produces an unbiased estimate of the ensemble-average equal-time current cross-correlation function,

\[ \langle \hat{C}(\rho_1) \rangle = \langle i_1(t) i_2(t) \rangle = q^2 \eta^2 A_1 \]

\[ \times \int_{A_2} d\rho \int du_1 \int du_2 \rho_B(t - u_1) \rho_B(t - u_2) \]

\[ \times \langle \hat{E}_1^\dagger(\rho, u_1) \hat{E}_1(\rho, u_2) \hat{E}_1(\rho, u_1) \hat{E}_2(\rho, u_2) \rangle. \]

(11)

We have used the commutation relations (1) and (2) to put the integrand into normal order. Next, the Gaussian-state moment-factoring theorem is utilized to the fourth-order moment\cite{13,22,31}, replacing the fourth-order moment with expressions that depend only on the second-order moments of the light fields,

\[ \langle \hat{C}(\rho_1) \rangle = q^2 \eta^2 A_1 \]

\[ \times \int_{A_2} d\rho \int du_1 \int du_2 \rho_B(t - u_1) \rho_B(t - u_2) T(\rho_1) \]

\[ \times \left( \langle \hat{E}_1^\dagger(\rho_1, u_1) \hat{E}_1(\rho_1, u_1) \hat{E}_1^\dagger(\rho_2, u_2) \hat{E}_2(\rho_2, u_2) \rangle \right) \]

\[ + \left| \langle \hat{E}_1^\dagger(\rho_1, u_1) \hat{E}_2(\rho_2, u_2) \rangle \right|^2. \]

(12)

For thermal light, the signal and reference fields have the maximum phase-insensitive cross correlation but no phase-sensitive cross correlation\cite{12,13,22}. In far field\cite{13,32}, we obtain the maximum phase-insensitive correlation function. The auto-correlation of the two detectors is given by

\[ \langle \hat{E}_m^\dagger(\rho_m, t) \hat{E}_m(\rho_m, t) \rangle \]

\[ = \frac{2P_m}{\pi a_L^2} e^{-2(\rho_m^2 + \rho_m^2)/a_L^2} e^{-|\rho_m - \rho_m|^2/2a_L^2}, \]

(13)

where \( m = 1, 2 \). The cross-correlation is expressed as

\[ \langle \hat{E}_1^\dagger(\rho_1, t_1) \hat{E}_2(\rho_2, t_2) \rangle \]

\[ = \frac{2P_3}{\pi a_L^2} e^{-(\rho_1^2 + \rho_2^2)/a_L^2} e^{-|\rho_2 - \rho_2|^2/2a_L^2}, \]

(14)

\[ P_n = \int_{R^2} d\rho \rho_B(\hat{E}_m^\dagger(\rho, t) \hat{E}_m(\rho, t)) \] is the photon flux\cite{6,32}, \( n = 1, 2, 3 \) and \( m, l = 1, 2 \). Substitute Eqs. (13) and (14) into Eq. (12). When the intensity radius \( a_L \) is much larger than the object’s transverse extent, the entire object is uniformly illuminated on average. Thus, we obtain the final form for the ensemble averaged photocurrent cross correlation,

\[ \langle \hat{C}(\rho_1) \rangle = \frac{q^2 \eta^2 A_1 A_2}{L^2} 4P_1 P_2 \]

\[ + \left( \frac{2P_3}{\pi a_L^2} \right)^2 \] \[ \int d\rho_2 e^{-|\rho_2 - \rho_2|^2/2a_L^2} T(\rho_2). \]

(15)

The ghost image term can be seen as the object's intensity-reflection coefficient \( T(\rho_2) \) convolved with a Gaussian point spread function.
Indeed, the only difference between Eq. (20) and the corresponding result for the reflective ghost imaging is the photon flux $P_3$.

The SNR of ghost imaging is defined as

$$\text{SNR} = \frac{(\tilde{C}(\rho_1))^2}{\langle \Delta C^2(\rho_1) \rangle},$$

where $\Delta C(\rho) \equiv \tilde{C}(\rho) - \langle \tilde{C}(\rho) \rangle$. We can obtain the expression of SNR,

$$\text{SNR} = \frac{T^2(\rho_1) T_1 / T_0}{\frac{A_T}{\sqrt{2\pi a_L^2}} + \frac{T^2(\rho_1) T_1 \Gamma a_0^2}{4\pi T_0 A_2}} + \frac{T(\rho_1) L^2}{\eta T A_2} + \frac{4\pi a_L^2 T(\rho_1)}{3A_1 \eta T} + \frac{\sqrt{\pi} \Omega B T_0 a_0^2 T(\rho_1) L^2}{16\sqrt{2} A_1 A_2 \eta T^2},$$

where, $\Gamma \equiv P_3 T_0 a_0^2 / a_L^2, A_T = \int dp_2 |T(p_2)|^2, \Gamma = \pi \int_{|v| \leq 4L} d\nu e^{-|\nu|^2/2} O(\nu), \nu = \rho L k_0 (\rho' - \rho'')$ is the difference coordinates, $\rho'$ and $\rho''$ are the coordinates at the bucket detector.

The ghost image comes from the intensity cross-correlation function. Therefore, the SNR of thermal ghost image depends on the light intensity of source. Moreover, the SNR also depends on the splitting ratio of the beam splitter because $P_3 = \sqrt{\alpha^2 (1 - \alpha) I_0}$. Fortunately, we can obtain a reflective ghost image with high image quality by adopting a low light intensity signal beam and a high light intensity reference beam achieved by changing the splitting ratio. Figure 2 shows that the SNR of ghost imaging will increase with the increase of the light intensity of source. The SNR is dramatically enhanced when the light intensity is not very strong. However, the enhancement of the SNR is not dramatically when the light intensity continues to increase. Therefore, a source with reasonable light intensity is necessary to obtain the ghost image with high SNR, which is very important for ghost imaging in practical application.

Moreover, we have also analyzed the case of ghost imaging with quantum source. We find that the quantum case is similar to the thermal case including the brightness, image contrast and SNR. The SNR will also increase with the increase of light intensity of quantum source because the relationship between the SNR of ghost imaging with thermal and quantum source and total correlations is a quasi-linear ratio. Of course, both the SNR and total correlations are bounded at high illumination.

In conclusion, our research work shows that the brightness of reflective ghost image can be changed by modulating the light intensity of the source and the splitting ratio of beam splitter. In this scheme of reflective ghost imaging, the image contrast is not dramatically when the light intensity continues to increase of the light intensity of source. Therefore, the enhancement of the SNR is not very strong. However, the enhancement of the SNR is not dramatically when the light intensity continues to increase. Therefore, a source with reasonable light intensity is necessary to obtain the ghost image with high SNR, which is very important for ghost imaging in practical application.
ratio of the beam splitter. The SNR depends on the light intensity of source, and can be changed by the splitting ratio. However, the image contrast of the reflective ghost image does not affect by the light intensity. More important, we find another advantage of ghost imaging compared with classical optical imaging, i.e., a ghost image with high brightness, high image contrast, and high SNR can be obtained by using a low light intensity signal beam and a high light intensity reference beam, which can reduce the effects of light on the object. This is very useful in biology.

This work was supported by the National Natural Science Foundation of China (Nos. 11204156, 61178012, 11304179, and 11247240). The Specialized Research Fund for the Doctoral Program of Higher Education (No. 20123705120002).

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