Rapid Communication

High-order ghost imaging with N-colour thermal light*

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High-order ghost imaging with thermal light consisting of N different frequencies is investigated. The high-order intensity correlation and intrinsic correlation functions are derived for such N-colour light. It is found that they are similar in form to those for the monochromatic case, thus most of the conclusions we obtained previously for monochromatic Nth-order ghost imaging are still applicable. However, we find that the visibility of the N-colour ghost image depends strongly on the wavelength used to illuminate the object, and increases as this wavelength increases when the test arm is fixed. On the contrary, changes of wavelength in the reference arms do not lead to any change of the visibility.

Keywords: ghost imaging, high-order intensity correlation, intrinsic high-order correlation, multi-colour thermal light

PACC: 4225K, 4230, 4250

1. Introduction

Ghost imaging (GI)[1] is a type of nonlocal imaging technique which requires joint intensity (i.e., second-order intensity correlation) measurements of light between two separate points. Over the past decade, this technique has inspired considerable interest[2] on account of its many promising applications, such as quantum lithography,[3−5] quantum holography,[6] quantum optical coherence tomography,[7] and lensless imaging.[8−11] Although most of these applications can also be realized by means of conventional imaging methods, GI has still attracted much attention in recent years on account of its many advantages, such as high-resolution,[12] minimum distortion,[13] and dispersion cancellation.[7] Historically, this effect was discussed as early as 1988,[14] and was first observed by Shih's group[1] using spatially entangled photon pairs. Later, it attracted great attention when traditional classical light sources were employed.[2,15] Today, the fundamental physics behind this phenomenon is still under debate,[16−20] but no matter whether it is purely quantum or classical, the experimental observations and their relevance to application will still hold.

In recent years, higher-order GI with monochromatic thermal light has been widely studied[21−27] mainly due to the fact that it can produce high-visibility images. Among these studies, our group was the first to draw attention to the role of N-photon bunching in the Nth-order GI schemes.[26] We showed that it is the contribution of this N-photon bunching which truly characterises the Nth-order intensity correlation and leads to enhanced high visibility in Nth-order GI.[26] Several experiments[22,27] have also been reported that lend support to our previous theoretical analysis. In another development, Chan *et al.*, recently studied the properties of two-colour GI with thermal light and showed theoretically that the resolution of nondegenerate wavelength thermal GI can be higher than its quantum counterpart.[28] Considering the above, we feel that a more complete discussion of high-order GI with N-colour thermal light is necessary. In this paper, we extend our previous treatment of Nth-order GI from the monochromatic case to a more general N-colour case. We derive the Nth-order intensity correlation and intrinsic Nth-order correlation functions for N-colour thermal light, then use them to discuss the existence conditions for N-colour GI. Although they have similar forms to those that we obtained previously for Nth-order monochromatic ghost imaging, we show that the visibility depends significantly on the wavelength used to illuminate the object. As this wavelength increases (decreases), the

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image visibility increases (decreases) as well when the test arm is fixed. However, any changes of wavelength in the reference arms do not lead to any change of the visibility.

2. Nth-order coherence of light with Gaussian statistics

In this section we briefly review some fundamental concepts concerning the high-order spatial coherence of light. More details may be found in Refs. [26], [29] and [30]. The equal-time Nth-order intensity correlation function $G^{(N)}_{1,\ldots,N}$ among N space–time points (y_i,t) $(i=1,\ldots,N)$ is undoubtedly the most important quantity in high-order spatial correlation measurements. It is usually defined by

$$G^{(N)}_{1,\ldots,N}=\left\langle\prod_{i=1}^{N}I_i(y_i,t)\right\rangle \tag{1}$$

with its normalised form

$$g^{(N)}_{1,\ldots,N}=\frac{G^{(N)}_{1,\ldots,N}}{\prod_{i=1}^{N}\langle I_i(y_i,t)\rangle}, \tag{2}$$

where $I_i(y_i,t)=|E_i(y_i,t)|^2$ is the instantaneous intensity at (y_i,t).

Generally, the calculation of $G^{(N)}_{1,\ldots,N}$ or $g^{(N)}_{1,\ldots,N}$ for arbitrary orders is difficult mathematically. But fortunately, for the case where the field $E_i(y_i,t)$ obeys Gaussian statistics, Eqs. (1) and (2) can be easily expressed in terms of the first-order field correlation as[29]

$$G^{(N)}_{1,\ldots,N}=\sum_{P}\prod_{i=1}^{N}G^{(1)}_{i,Pi}, \tag{3}$$

$$g^{(N)}_{1,\ldots,N}=\sum_{P}\prod_{i=1}^{N}g^{(1)}_{i,Pi}, \tag{4}$$

where $G^{(1)}_{i,j}=\langle E^*_i(y_i,t)E_j(y_j,t)\rangle$, $g^{(1)}_{i,j}=G^{(1)}_{i,j}/\sqrt{\langle I_i(y_i,t)\rangle\langle I_j(y_j,t)\rangle}$, and the sum runs over all the $N!$ possible permutations $P: i\to Pi$ of the integers $i=1,\ldots,N$.

Since $G^{(N)}_{1,\ldots,N}$ (or $g^{(N)}_{1,\ldots,N}$) inevitably contains some lower-order contributions besides the pure Nth-order (N-photon bunching) correlations, in 1970 Cantrell[30] introduced a quantity called the intrinsic Nth-order correlation, to describe only the pure Nth-order correlation effect for light with Gaussian statistics, i.e.,

$$K^{(N)}_{1,\ldots,N}=\sum_{C}\prod_{i=1}^{N}G^{(1)}_{i,Ci}, \tag{5}$$

and its normalised form

$$\kappa^{(N)}_{1,\ldots,N}=\sum_{C}\prod_{i=1}^{N}g^{(1)}_{i,Ci}, \tag{6}$$

where the sum runs over all $(N-1)!$ cyclic permutations C of the integers $i=1,\ldots,N$.

For the two lowest-order cases, i.e., $N=2,3$, from Eqs. (4) and (6), it is easy to obtain

$$\kappa^{(2)}_{1,2}=\left|g^{(1)}_{1,2}\right|^2, \tag{7}$$

$$\kappa^{(3)}_{1,2,3}=2\mathrm{Re}[g^{(1)}_{1,2}g^{(1)}_{2,3}g^{(1)}_{3,1}], \tag{8}$$

$$g^{(2)}_{1,2}=1+\kappa^{(2)}_{1,2}, \tag{9}$$

$$g^{(3)}_{1,2,3}=1+\kappa^{(2)}_{1,2}+\kappa^{(2)}_{1,3}+\kappa^{(2)}_{2,3}+\kappa^{(3)}_{1,2,3}. \tag{10}$$

3. Theory of N-colour ghost imaging with thermal light

The correlated thermal light beams used for GI need not have the same wavelength. However, since no spatial intensity correlation exists between different frequencies for true thermal light, N-colour GI cannot be performed with it. To produce the desired N-colour thermal light, we follow the method used in Ref. [28], that is, N quasi-monochromatic laser beams with central frequencies $\Omega_j(j=1,\ldots,N)$ are made to coincide with each other and pass through a spatial light modulation system which impresses an identical random amplitude modulation $V(x)$ with Gaussian statistics onto each beam. In this way, the resulting N-colour light is rendered spatially incoherent but in a correlated fashion.

Figure 1 shows a general N-colour ghost imaging system that consists of a beamsplitter device that splits an N-colour beam into N separate monochromatic beams of central frequency Ω_j which travel a distance z_j to detectors D_j. A test arm contains an unknown object illuminated by E_1, and $(N-1)$ reference arms are illuminated by $E_2,\ldots,E_N$, respectively. If each source field is taken to be a plane wave with spectrum $f_j(\nu)$, after traversing the spatial light modulator (SLM) it can be represented by $E_j(x,\nu)=f_j(\nu)V(x)$, where ν is the frequency variable, x the transverse coordinate in the SLM plane, and $f_1,\ldots,f_N$ are mutually independent. Thus, the fields at the detection planes can be expressed as

$$E_j(y_j,t)=\int \mathrm{d}\nu_j\,\mathrm{d}x E_j(x,\nu_j)\,\mathrm{e}^{-\mathrm{i}\nu_j t}h_j(y_j,x;\nu_j), \tag{11}$$

where $h_j(y_j, x; \nu_j)$ is the impulse response function describing the corresponding propagation of beam (ν_j). Considering the quasimonochromaticity of each beam, in the following calculation we can approximate $h_j(y_j, x; \nu_j)$ with $h_j(y_j, x; \Omega_j)$. In addition, for simplicity, we only consider the one-dimensional transverse position y_j of the detectors.

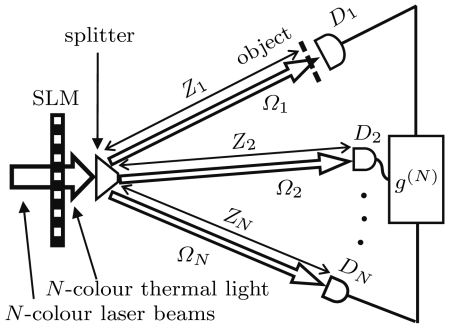


Fig. 1. Schematic of an N-colour ghost imaging system. SLM: spatial light intensity modulator; splitter: an optical device that splits an N-colour beam into N separate monochromatic beams; D_1 is a bucket detector, whereas $D_2, \ldots, D_N$ represent $(N-1)$ point detectors at transverse positions $y_2, \ldots, y_N$, respectively.

If we further take $V_j(y_j) = \int \mathrm{d}x V(x) h_j(y_j, x; \Omega_j)$, which also obeys Gaussian statistics, and $F_j(t) = \int \mathrm{d}\nu_j f_j(\nu_j)\, \mathrm{e}^{-\mathrm{i}\nu_j t}$ to represent the spatial and temporal components of the field $E_j(y_j, t)$, respectively, then Eq. (11) can be put into a more compact form as

$$E_j(y_j, t) = V_j(y_j) F_j(t). \tag{12}$$

By substituting Eq. (12) into Eq. (1), and making use of Eq. (3), the Nth-order joint intensity $G^{(N)}_{1,\ldots,N}$, which is the measured quantity in N-colour GI experiments, can be expressed in terms of $V_j(y_j)$ as

$$\begin{aligned} G^{(N)}_{1,\ldots,N} &= \left\langle \prod_j^N |F_j(t) V_k(y_k)|^2 \right\rangle \\ &= \left\langle \prod_j^N |F_j(t)|^2 \right\rangle \left\langle \prod_k^N |V_k(y_k)|^2 \right\rangle \\ &= A \sum_P \prod_k^N \langle V_k^*(y_k) V_{Pk}(y_{Pk}) \rangle, \end{aligned} \tag{13}$$

and its normalised form

$$g^{(N)}_{1,\ldots,N} = \sum_P \prod_k^N \Gamma^{(1)}_{k,Pk}, \tag{14}$$

where $A = \prod_j^N \left\langle |F_j(t)|^2 \right\rangle$ is the product of the average intensities of all N beams of light incident on the SLM, and $\Gamma^{(1)}_{i,j}$ is the normalised form of $\langle V_i^*(y_i) V_j(y_j) \rangle$. The propagation of the quantity $\langle V_i^*(y_i) V_j(y_j) \rangle$ satisfies the following formula:

$$\begin{aligned} &\langle V_i^*(y_i) V_j(y_j) \rangle \\ &= \int \mathrm{d}x \mathrm{d}x' \, \langle V^*(x) V(x') \rangle \, h_i^*(y_i, x; \Omega_i) h_j(y_j, x; \Omega_j), \end{aligned} \tag{15}$$

where $\langle V^*(x) V(x') \rangle$ reflects the spatial coherence of the fields in the source (SLM) plane. However, we should remember that $V(x)$ is only the spatial component of the light field, so in fact the optical fields of two arbitrary arms are not wholly correlated, i.e., $\langle E_i^*(y_i, t) E_j(y_j, t) \rangle = \langle F_i^* F_j \rangle \langle V_i^* V_j \rangle = 0, (i \neq j)$.

Then, according to Cantrell's theory[30] and using Eqs. (13) and (14), the intrinsic Nth-order correlation function and its normalised form for such an N-colour GI system can be written, respectively, as

$$K^{(N)}_{1,\ldots,N} = A \sum_C \prod_k^N \langle V_k^*(y_k) V_{Ck}(y_{Ck}) \rangle, \tag{16}$$

and

$$\kappa^{(N)}_{1,\ldots,N} = \sum_C \prod_k^N \Gamma^{(1)}_{k,Ck}. \tag{17}$$

It should be noted that in the process of working out Eqs. (13) and (14) and Eqs. (16) and (17), it is $V_j(y_j)$ rather than $E_j(y_j, t)$ that follows Gaussian statistics, so we cannot directly use Eqs. (3) and (4) and Eqs. (5) and (6) to describe the complete field $E_j(y_j, t)$. Otherwise, owing to the lack of correlation between the fields, there will be no Nth-order intensity correlation, to say nothing of the intrinsic correlation, for N-colour light. On the other hand, it is precisely this point that reflects the difference between the usual monochromatic high-order and multicolour GI. For the former, since field correlations exist between two arbitrary arms, it seems reasonable to attribute the Nth-order ghost image to the contributions of the first-order correlations since the Nth-order correlation can be expanded in terms of the first-order correlations. However, for the N-colour GI analysed above, first-order correlation exists only between the spatial components of fields (see Eq. (15)) and not in the optical fields themselves, so we cannot explain N-colour GI in the same way, and it cannot be reproduced with any interferometer based on the first-order correlation of light.

Equations (14) and (17) are the two most important results in this paper, which reflect, respectively, the Nth-order intensity correlation and intrinsic Nth-order correlation for N-colour thermal light. With these two expressions, we can derive the N-colour

ghost image so long as certain indispensable imaging conditions are satisfied. By comparison with the monochromatic case, based on our previous work, it is not difficult to guess that the relevant imaging conditons should also contain two aspects. The first is that the second-order imaging equation, such as the two-photon Guassian thin lens equation, or the lensless imaging or diffraction equation, must be satisfied between the test arm and each reference arm. This is a prerequisite for any type of GI. Moreover, as we have pointed out in the monochromatic case, the configuration of the different reference arms need not be the same. The second requirement is the synchronous detection of all reference detectors, i.e., $y_2 = y_3 = \cdots = y_N$, which ensures that the contribution from the N-photon bunching exists and that each term in Eq. (14) contributes effectively to the final ghost image. Under these two conditions, we can obtain

$$g^{(N)}_{1,\ldots,N} = (N-1)!\left[1 + (N-1)\xi\left|t(\gamma y_i)\right|^2\right], \quad (18)$$

$$\kappa^{(N)}_{1,\ldots,N} = (N-1)!\xi\left|t(\gamma y_i)\right|^2, \quad (19)$$

$$\sum_{n}^{N-1} \kappa^{(N-1)}_{n} = \kappa^{(N)}_{1,\ldots,N}, \quad (20)$$

where ξ is a constant, $1/\gamma$ the magnification of the image, and t the object's transmission function. Equation (18) is very similar to the expression for two-colour (or second-order imaging) : $g^{(2)}_{1,2} = 1 + \kappa^{(2)}_{1,2}$, except that the ratio of the background to the effective imaging term is different in the two cases. The background term $(N-1)!$ originates from the mth-order ($m = 2, \ldots, N-1$) correlations among m reference arms which contain no information about the object, together with the accidental correlation among the N beams. The effective imaging term $(N-1)!(N-1)\xi\left|t(\gamma y_i)\right|^2$ comes from the kth ($k = 2, \ldots, N$) correlations among k arms including the test arm. Although the background $(N-1)!$ increases with N, its value is always smaller than the effective imaging term by a factor of $1/(N-1)$, which shows that the visibility of N-colour ghost imaging can still be enhanced when N is sufficiently large. In Eq. (19), $\kappa^{(N)}_{1,\ldots,N}$ describes the contribution from the N-photon bunching effect to the Nth-order ghost image, the distinctive feature of N-colour GI. Equation (20) reflects the fact that this contribution is not at all small but is equal to the sum of all the contributions from $(N-1)$-photon bunching. In this regard, high-order GI with N-colour light requires the same imaging conditions as those of the usual monochromatic case.

4. Numerical examples

To support our previous purely theoretical analysis, in this section we shall give an example through numerical calculation. For simplicity but without loss of generality, only the three-colour case will be considered. We choose the example of three-colour lensless GI, which can be illustrated by Fig. 1, where only one test arm and two reference detectors are considered, illuminated by light beams of wavelength λ_1 and λ_j ($j = 2, 3$), respectively. The relevant impulse response functions are given by Ref. [11]

$$h_1(y_1, x; \lambda_1) = \exp\left[\frac{\mathrm{i}\pi}{\lambda_1 z_1}(x - y_1)^2\right] t(y_1), \quad (21)$$

$$h_j(y_j, x; \lambda_j) = \exp\left[\frac{\mathrm{i}\pi}{\lambda_j z_j}(x - y_j)^2\right], (j = 2, 3) \quad (22)$$

for the test and reference arms, respectively, where some unessential constant phase factors have been omitted. In addition, we assume the light at the output surface of the SLM to be uniform and completely incoherent, i.e., $\langle V^*(x)V(x')\rangle = \delta(x - x')$. This simplification will not influence the fundamental physics behind the phenomenon.

For comparison with possible future experiments, all the parameters in our mumerical calculation are chosen to be easily realizable experimentally. The transverse size S of all the required three laser beams and their wavelengths are taken to be $S = 3$ mm and $\lambda_1 = 442$ nm, $\lambda_2 = 532$ nm, and $\lambda_3 = 633$ nm, respectively. The object is taken to be a double-slit of slit-width 100 μm and slit-separation 300 μm. The three-colour lensless GI equation $\lambda_1 z_1 = \lambda_2 z_2 = \lambda_3 z_3$ is satisfied by setting $z_1 = 120$ mm, $z_2 = 100$ mm and $z_3 = 84$ mm.

From Eqs. (14) and (17), we know that the normalised third-order intensity correlaton can be written as $g^{(3)}_{1,2,3} = 1 + \kappa^{(2)}_{2,3} + \kappa^{(2)}_{1,2} + \kappa^{(2)}_{3,1} + \kappa^{(3)}_{1,2,3}$ which is the same as Eq. (10). On the right-hand side of Eq. (10), the two first terms denote the background, the middle two the second-order effects, and the last term describes the three-photon bunching effect. Since we wish to focus on the contribution from three-photon bunching and its role in three-colour GI, we provide a comparison of the contributions from the two-photon and three-photon effects. Figure 2 shows the sum of the two second-order (two-photon bunching) effects $\kappa^{(2)}_{1,2} + \kappa^{(2)}_{3,1}$, calculated under synchronous detection $y_2 = y_3$. Figure 3 presents $\kappa^{(3)}_{1,2,3}$ plotted against arbitrary y_2 and y_3. It is clear from these figures that the

contribution from three-photon bunching exists noticeably only in the neighbourhood of $y_2 = y_3$, which is just the synchronous detection condition. Moreover, the contribution from three-photon bunching to the final imaging is equal to the sum of the contributions from the two-photon effects, which concurs with the conclusions obtained in the previous section.

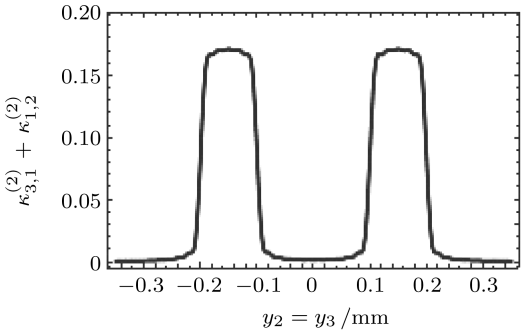


Fig. 2. The sum of the contributions from two-photon bunching to three-colour lensless GI under synchronous detection.

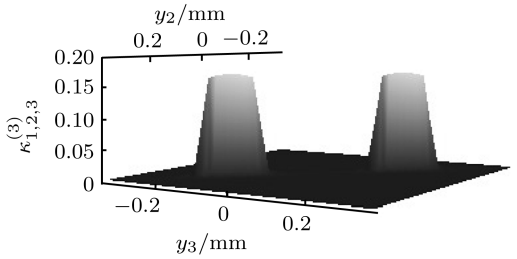


Fig. 3. Contribution from three-photon bunching to three-color lensless GI.

Now let us investigate the influence of the beam wavelengths on the imaging visibility. For simplicity, we still take the three-colour case as example, but the generalisation to the N-colour case is straightforward. For three-colour GI, the visibility can be defined as

$$v^{(3)} = \frac{g^{(3)}_{\max} - g^{(3)}_{\min}}{g^{(3)}_{\max} + g^{(3)}_{\min}}. \tag{23}$$

Since the two reference arms are in essence equivalent, only one needs to be calculated. With the test arm the same as before (i.e., $z_1 = 120$ mm), the dependences of the visibility on λ_2 and λ_1 are plotted in Figs. 4(a) and 4(b), respectively, on condition that $\lambda_1 z_1 = \lambda_2 z_2 = \lambda_3 z_3$ is still satisfied. From the two figures, it can be seen that the change of λ_2 (from 400 nm to 700 nm) does not lead to any change in the visibility, whereas when λ_1 increases (or decreases) the visibility increases (or decreases) as well. This means that the visibility depends merely on the wavelength used to illuminate the object. Why is this so? These phenomena can be explained by using the theory developed by Gatti *et al.* in Ref. [2]. Their paper showed that the visibility roughly scales as the ratio of the coherence area to the object's transmissive area: the larger the object's dimensions are with respect to the speckles, i.e., the more incoherent the light illuminating the object is, the poorer the visibility is. In our imaging system, since the transverse coherence length $l_{\rm coh}$ of the beam in the object plane is proportional to $z_1\lambda_1/S$,[29] as λ_1 increases, $l_{\rm coh}$ naturally becomes larger, thus the visibility increases as well. This conclusion is applicable not only to the three-colour GI example here but also to all arbitrary N cases.

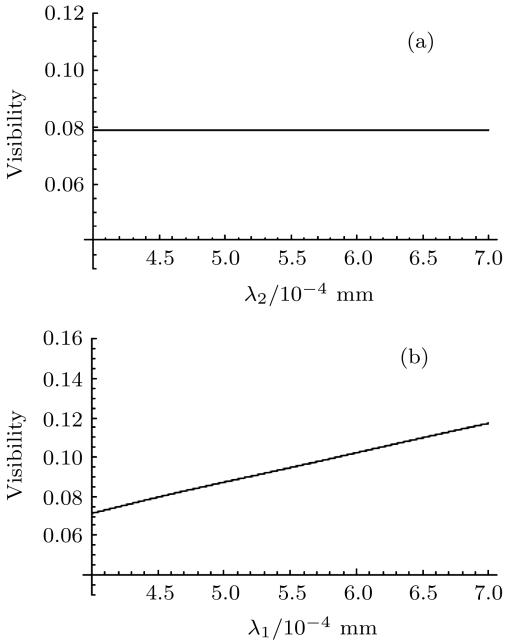


Fig. 4. Dependencies of the visibility on the (a) λ_2 and (b) λ_1.

5. Conclusion

We have theoretically investigated high-order ghost imaging with N-colour thermal light, and have derived the high-order intensity correlation and intrinsic correlation functions for such light. Since they have similar expressions to those for the monochromatic case, most of the qualitative conclusions obtained previously for high-order monochromatic GI are still applicable. In addition, the dependence of the image visibility on the wavelength of each beam has been studied. We find that the visibility of the N-colour ghost image depends strongly on the wavelength used

to illuminate the object; as this wavelength increases (decreases), the visibility increases (decreases) when the test arm is fixed. On the contrary, changing the wavelength in any of the reference arms does not lead to any change in the visibility. Our results may have important bearing on GI in which the optimal wavelength for illumination of the object is very different from the optimal wavelength for the detector.

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