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Proposal for observing intensity-intensity–correlation speckle patterns with thermal light via phase conjugation

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In traditional Hanbury Brown–Twiss (HBT) schemes, thermal intensity-intensity correlations (IICs) are phase insensitive. Here we propose a modified HBT scheme with phase conjugation to demonstrate phase-sensitive and nonfactorizable features of thermal IIC speckles. It shows that the novel phase-sensitive features originate from the correlation between the original and phase-conjugated thermal light. Our numerical simulation confirms the possibility of experimental realization, even for the cases of the imperfect phase conjugation. Unlike two-photon speckles, our scheme uses thermal light sources, not the entangled two-photon sources. Our result provides deeper insight into thermal correlations and may lead to significant applications in imaging and speckle technologies.

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Optical speckles usually refer to the random interference phenomenon, which happens when coherent light fields are reflected from (or pass through) a disordered scattering medium [1]. This phenomenon has been recognized to be the manifestation of random characteristics (e.g., randomly varying phase and amplitude) of a scattering medium. Various applications have been developed to make use of speckle phenomena in many fields ranging from astronomy to random lasers [1,2].

To observe optical speckles, one often needs a light source with good spatial coherence. It is widely believed that there is no speckle effect for thermal or incoherent light fields. The conventional speckles are usually described by the scattering intensity, which is regarded as a one-photon probability density. Recently, the concept of two-photon speckles, described via a two-photon probability density, was developed elegantly within the theory of quantum correlations [3,4]. The experiment of two-photon speckles was demonstrated via the coincidence measurements, which are also called as intensity-intensity–correlation (IIC) measurements [5–7]. These studies are important to directly visualize the spatial structure of entanglement in nonclassical scattering light.

There is a series of theoretical and experimental investigations [8–16] with pseudothermal or true thermal light on ghost imaging, ghost diffraction, and interference due to a certain similarity between a two-photon source and an incoherent light [17]. The physical properties of the correlations of thermal light fields are also interesting for different aspects [18–22]. Until now, the IIC speckles for thermal or incoherent light have remained unexplored since thermal correlations are usually phase insensitive [23]. It was discovered that the nonfactorizable feature in two-photon speckles is not present for thermal light [5]. In this Rapid Communication we propose a modified Hanbury-Brown–Twiss (HBT) scheme via phase conjugation to change thermal correlations for observing phase-sensitive IIC speckles and nonfactorizable features for thermal light.

Our scheme is different from those based on ghost imaging. The thermal photons in our case pass through a common transmission mask (TM) and the light source here is thermal light, not the two-photon entangled light. Our result shows that phase-sensitive IIC speckles for thermal light sources are realizable by modifying thermal correlations via phase conjugation.

We first briefly discuss the traditional HBT scheme [24,25] (see Fig. 1). One can see that light passes through the TM and then is divided into two paths by the beam splitter. It is known that, for thermal or incoherent sources obeying Gaussian statistics, the IIC function $C_T(x_1,x_2)$ is expressed by the Siegert relation [26]

$$C_T(x_1,x_2) = \langle I_T(x_1)\rangle\langle I_T(x_2)\rangle + |W_T(x_1,x_2)|^2, \quad (1)$$

where $\langle I_T(x_j)\rangle$ ($j = 1,2$) is the average intensity on the output planes 1 and 2 and $W_T(x_1,x_2)$ is the cross-spectral density between the two output planes [17]

$$\langle I_T(x_j)\rangle = \iint W_i(\nu_1,\nu_2)h_j^*(\nu_1,x_j)h_j(\nu_2,x_j)d\nu_1 d\nu_2, \quad (2)$$

$$W_T(x_1,x_2) = \iint W_i(\nu_1,\nu_2)h_1^*(\nu_1,x_1)h_2(\nu_2,x_2)d\nu_1 d\nu_2. \quad (3)$$

Here $W_i(\nu_1,\nu_2) \equiv \langle E_i^*(\nu_1)E_i(\nu_2)\rangle$ is the initial cross-spectral density of the input random light fields $E_i(\nu)$ at the TM. The impulse response functions $h_j(\nu,x_j)$, from the Collins formula, can be expressed as [27,28]

$$h_j(\nu,x_j) = t(\nu)\left(\frac{-i}{\lambda B_j}\right)^{1/2} e^{(i\pi/\lambda B_j)(A_j\nu^2-2\nu x_j+D_j x_j^2)} \quad (4)$$

under the paraxial approximation, where λ is the wavelength; A_j, B_j, and D_j are the elements of the 2×2 ray transfer matrices [29] $\begin{pmatrix} A_j & B_j \\ C_j & D_j \end{pmatrix}$ describing the linear optical systems

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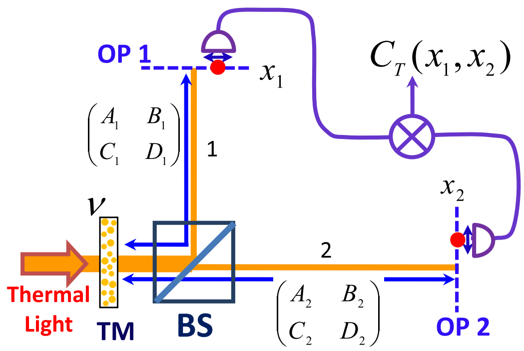

FIG. 1. (Color online) Traditional HBT scheme. The TM is in front of the beam splitter (BS) and the intensities on the output planes OP1 and OP2 are correlated by a correlator. Optical paths 1 and 2 from the TM to OP1 and OP2 are characterized by the 2×2 ray transfer matrices.

from the TM to the output planes; and $t(\nu)$ is the complex transmission coefficient of the TM.

For simplicity, both optical paths 1 and 2 are assumed to be within the range of Fraunhofer diffraction [28], i.e., $A_j = 0$. The input light is a thermal or incoherent source, i.e., $W_i(\nu_1,\nu_2) = I_0\delta(\nu_1 - \nu_2)$ with I_0 a constant. Therefore, $C_T(x_1,x_2)$ is written as

$$C_T(x_1,x_2) = \langle I_T(x_1)\rangle\langle I_T(x_2)\rangle[1 + \mu_T(x_1,x_2)], \quad (5)$$

where

$$\mu_T(x_1,x_2) = \frac{1}{N_0^2}\left|\mathcal{F}_1[|t(u)|^2]\left(\frac{x_2}{\lambda B_2} - \frac{x_1}{\lambda B_1}\right)\right|^2 \quad (6)$$

is the normalized phase-insensitive shape function. Here $\mathcal{F}_1$ denotes the one-dimensional Fourier transform of $|t(\nu)|^2$ with the argument of $\frac{x_2}{\lambda B_2} - \frac{x_1}{\lambda B_1}$ and $\langle I_T(x_j)\rangle = I_0 N_0(\lambda|B_j|)^{-1}$ with $N_0 = \int |t(\nu)|^2 d\nu$ a constant. In addition, $\mu_T(x_1,x_2)$ contains only partial information of $t(\nu)$, i.e., the amplitude of $t(\nu)$, and it has no phase information on $t(\nu)$. Therefore, the thermal IICs based on traditional HBT schemes are essentially phase insensitive [5,23].

In order to go beyond traditional HBT-based schemes, we propose an optical system to fulfill the phase-sensitive IIC scheme for thermal light, as shown in Fig. 2. In principle, through the optical systems in Fig. 2(a), thermal fields are essentially changed into the modified thermal source, which contains the phase-sensitive thermal correlations. A forward nondegenerate phase conjugation (PC) device [30] is inserted into the upper path at the ξ plane and generates the PC waves with wavelength λ_p (here $\lambda_p \neq \lambda$ in general cases). When $\lambda d_1 = \lambda_p d_2$, where d_1 is the distance from the input plane to the PC device and d_2 is that from the PC device to the TM, the random light at the TM via the upper path forms a conjugate image of input light, i.e., $E_{\nu,\mathrm{up}}(\nu) = \alpha E_i^*(\nu)$, where ν is the coordinate of the plane at the TM and α is the generating rate of the PC light. Note that the free-space propagations before and after the PC device can also be replaced by imaging systems (such as 4-f lens systems) and the PC process is assumed to be perfect. The lower path of Fig. 2(a) consists of two pairs of 4-f lens optical systems [31,32], so the light at the TM via the lower path is the same as the input fields, i.e.,

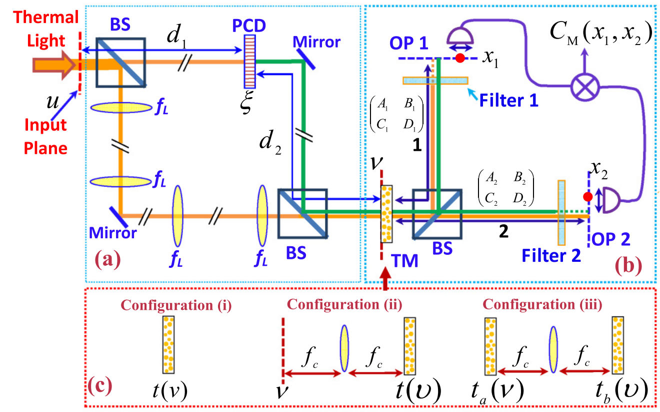

FIG. 2. (Color online) Modified HBT scheme for demonstrating the IIC speckles with phase-sensitive effects by using thermal light fields. (a) Modified thermal source at the incident plane ν of the TM. In the upper path of (a), random light fields pass through a forward nondegenerate PC device (PCD) and the optical distances d_1 and d_2 as shown in (a) are adjustable in order to form the PC fields of input light at the incident plane ν of the TM. In the lower path of (a), random light fields pass through two pairs of 4-f optical systems, which directly image the input thermal light fields onto the incident plane of the TM. (b) The IIC measurements similar to the case of Fig. 1, except for the filters added in each arm. (c) Three configurations (i)–(iii) displaying three different IIC speckles.

$E_{\nu,\mathrm{low}}(\nu) = E_i(\nu)$. The total light fields at the TM is given by $E_{\nu,\mathrm{t}}(\nu) = E_i(\nu) + \alpha E_i^*(\nu)$ [33]. Thus, correlations exist between the original random light fields and their PC fields that lead to the phase-sensitive contribution.

Figure 2(b) displays the measurement diagram of the IIC. The total light fields from the two paths of Fig. 2(a) pass through the common TM. Both paths from the TM to two output planes 1 and 2 also lie in the Fraunhofer region (i.e., $A_j = 0$) [28], similar to those in Fig. 1 except for additional optical filters. The IIC function in this modified system can be derived from its definition $C_M(x_1,x_2) \equiv \langle I_M(x_1)I_M(x_2)\rangle$ [34], where $I_M(x_{1,2})$ is the instantaneous intensity of each output plane. Filters 1 and 2 transmit the light fields of wavelength λ_p and λ, respectively, while blocking the remainder in each arm. Therefore, $C_M(x_1,x_2)$ is only contributed from the IICs between the scattering fields of both thermal light fields and their conjugated fields. The reason is that $I_M(x_{1,2})$ only contains the corresponding component of the light in each arm due to the role of each filter. Thus, $C_M(x_1,x_2)$ is simply written as

$$C_M(x_1,x_2) = \langle I_M(x_1)\rangle\langle I_M(x_2)\rangle\big[1 + \mu_M^{(p)}(x_1,x_2)\big], \quad (7)$$

where $\mu_M^{(p)}(x_1,x_2)$ is the normalized phase-sensitive shape function and depends on the detailed configuration of the optical system containing TMs [see Fig. 2(c)]. The expression for $\mu_M^{(p)}(x_1,x_2)$ is given by

$$\mu_M^{(p)}(x_1,x_2) = |W_M(x_1,x_2)|^2/[\langle I_M(x_1)\rangle\langle I_M(x_2)\rangle], \quad (8)$$

where

$$W_M(x_1,x_2) = \alpha \iint W_i(\nu_1,\nu_2)h_1(\nu_1,x_1)h_2(\nu_2,x_2)d\nu_1 d\nu_2 \tag{9}$$

is the phase-sensitive cross-spectral density between two output planes. Equation (9) is clearly different from Eq. (3). In fact, $\mu_M^{(p)}(x_1,x_2)$ determines the main behavior of $C_M(x_1,x_2)$ since the common factor $\langle I_M(x_1)\rangle\langle I_M(x_2)\rangle$ is separable. In more general cases, if the filters in Fig. 2(b) are removed (or disabled when $\lambda_p = \lambda$), then both phase-sensitive and phase-insensitive terms occur in Eq. (7), although this may increase the complexity to determine the phase-sensitive patterns.

Now we present the results of the three configurations, as shown in Fig. 2(c). The calculation process is tedious but straightforward and can be found in Ref. [35].

In configuration (i), the TM is located at the common imaging position in both paths of Fig. 2(a). Then $\mu_M^{(p)}(x_1,x_2)$ in Eq. (7) is given by

$$\mu_M^{(p)}(x_1,x_2) = \frac{1}{N_0^2}\left|\mathcal{F}_1[t^2(\nu)]\left(\frac{x_1}{\lambda_p B_1} + \frac{x_2}{\lambda B_2}\right)\right|^2. \tag{10}$$

The modified IIC in this case contains all phase-sensitive information on $t(\nu)$ since $|t(\nu)|^2$ is replaced by $t^2(\nu)$ in $\mu_M^{(p)}(x_1,x_2)$. The average intensities $\langle I_M(x_1)\rangle = I_0 N_0 \alpha^2(\lambda_p|B_1|)^{-1}$ and $\langle I_M(x_2)\rangle = I_0 N_0(\lambda|B_2|)^{-1}$ are constants and can be subtracted from $C_M(x_1,x_2)$. For $\lambda_p B_1 = \lambda B_2$, $\mu_M^{(p)}(x_1,x_2)$ is a function of the coordinate summation $x_1 + x_2$. This is similar to that of two-photon speckles in Ref. [5].

In configuration (ii), the TM is at the exit plane of a 2-f Fourier optical system [31,32] with the focus length f_c, so $\mu_M^{(p)}(x_1,x_2)$ is given by

$$\mu_M^{(p)}(x_1,x_2) = \frac{\lambda_p}{\lambda N_0^2}\left|\mathcal{F}_1[\Omega(\upsilon)]\left(\frac{x_2}{\lambda B_2} - \frac{x_1}{\lambda B_1}\right)\right|^2, \tag{11}$$

where $\Omega(\upsilon) = t(\upsilon)t(-\frac{\lambda_p}{\lambda}\upsilon)$ is a phase-sensitive function. The phase-sensitive effect here is embedded in the Fourier transformation of $\Omega(\upsilon)$. The average intensities are the same as that of configuration (i). Different from the previous case, when $B_1 = B_2$, Eq. (11) becomes a function of the coordinate subtraction $x_2 - x_1$, which is also similar to that of two-photon speckles in Ref. [5].

For configuration (iii), the two TMs are located at the incident and exit planes of the 2-f Fourier optical system. This configuration mimics a volume scatterer as mentioned in Ref. [5]. By a tedious but straightforward calculation, $\mu_M^{(p)}(x_1,x_2)$ is given by

$$\mu_M^{(p)}(x_1,x_2) = \frac{|\mathcal{F}_2[\Theta_p(\upsilon_1,\upsilon_2)](x_1/\lambda_p B_1, x_2/\lambda B_2)|^2}{S(x_1)S(x_2)}, \tag{12}$$

where $\mathcal{F}_2$ denotes a two-dimensional Fourier transform, $\Theta_p(\upsilon_1,\upsilon_2) = f_c^{-1}(\lambda_p\lambda)^{-1/2}t_b(\upsilon_1)t_b(\upsilon_2)\mathcal{F}_1[t_a^2(\nu)](\frac{\upsilon_1}{\lambda_p f_c} + \frac{\upsilon_2}{\lambda f_c})$, and $S(x_j) = \mathcal{F}_2[\Theta_{n,j}(\upsilon_1,\upsilon_2)](-\frac{x_j}{\lambda_j B_j}, \frac{x_j}{\lambda_j B_j})$ with $\Theta_{n,j}(\upsilon_1,\upsilon_2) = (\lambda_j f_c)^{-1}t_b^*(\upsilon_1)t_b(\upsilon_2)\mathcal{F}_1[|t_a(\nu)|^2](\frac{\upsilon_2-\upsilon_1}{\lambda_j f_c})$. Here $t_a(\nu)$ and $t_b(\upsilon)$ are the complex transmission coefficients for two TMs, respectively. The average intensities $\langle I_M(x_1)\rangle = \alpha^2 I_0(\lambda_p|B_1|)^{-1}S(x_1)$ and $\langle I_M(x_2)\rangle = I_0(\lambda|B_2|)^{-1}S(x_2)$ are not constants any more. The function $\Theta_p(\upsilon_1,\upsilon_2)$ includes all phase information on both $t_a(\nu)$ and $t_b(\upsilon)$, while $\Theta_{n,j}(\upsilon_1,\upsilon_2)$ is phase insensitive (only related to the average intensities). The difference between $\Theta_p(\upsilon_1,\upsilon_2)$ and $\Theta_{n,j}(\upsilon_1,\upsilon_2)$ is the key point for the volume scattering phenomenon, which generates the phase-sensitive effect of the IIC speckle patterns. Note that the background term $\langle I_M(x_1)\rangle\langle I_M(x_2)\rangle$ can still be subtracted from the IIC, like the situations in thermal ghost imaging and interference [8–10,36].

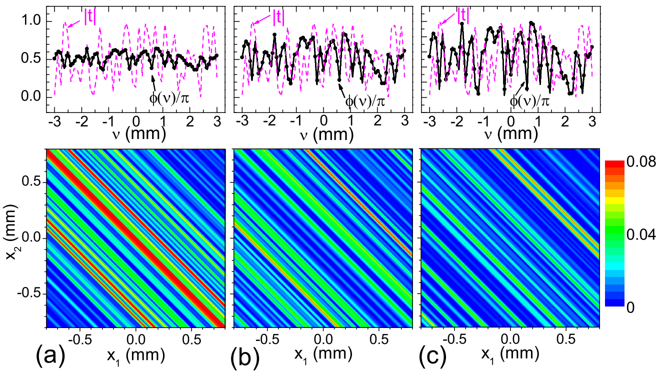

FIG. 3. (Color online) Different distributions of $\mu_M^{(p)}(x_1,x_2)$ for three different random diffusers in configuration (i) of Fig. 2(c). The corresponding upper parts show the amplitude $|t(\nu)|$ and phase $\phi(\nu)$ distributions of three different TMs. Other parameters are $\lambda_p B_1 = \lambda B_2 = 0.25$ mm^2.

We now discuss the IIC speckle patterns of modified thermal light passing through different configurations. Figure 3 shows the effect of the phase distribution of $t(\nu)$ on $\mu_M^{(p)}(x_1,x_2)$ for three different diffusers in configuration (i). In Figs. 3(a)–3(c) the distributions of $|t(\nu)|$ are the same, while their phases are totally different. It can be seen that the patterns of $\mu_M^{(p)}(x_1,x_2)$ vary with changing phase distributions. The enhancement of the phase-distribution randomness may lead to the more homogeneous interference speckle patterns with smaller average speckle size.

In Fig. 4 we demonstrate the patterns of $\mu_M^{(p)}(x_1,x_2)$ for the diffusers in configurations (ii) and (iii). Here $t(\nu)$ is the same as that in Fig. 3(c). In contrast to Fig. 3(c), the pattern in Fig. 4(a) is along the coordinate subtraction $x_1 - x_2$ but not along the coordinate summation $x_1 + x_2$. These phase-sensitive effects cannot happen in traditional HBT schemes with thermal light, but here they do occur. In Figs. 4(b) and 4(c) the patterns of $\mu_M^{(p)}(x_1,x_2)$ for configuration (iii) mimic the volume scatterer

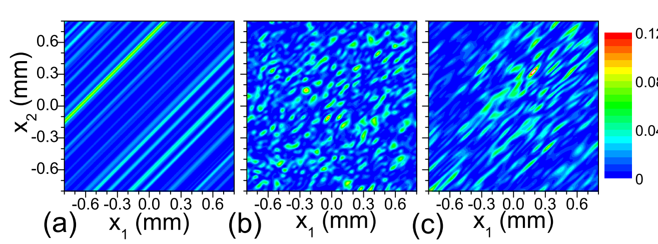

FIG. 4. (Color online) Distributions of $\mu_M^{(p)}(x_1,x_2)$ for the random diffusers in (a) configuration (ii) and (b) and (c) configuration (iii). Other parameters are $\lambda_p = 550$ nm, $\lambda = 500$ nm, $B_1 = B_2 = 500$ mm, and (b) $f_c = 500$ mm and (c) $f_c = 150$ mm.

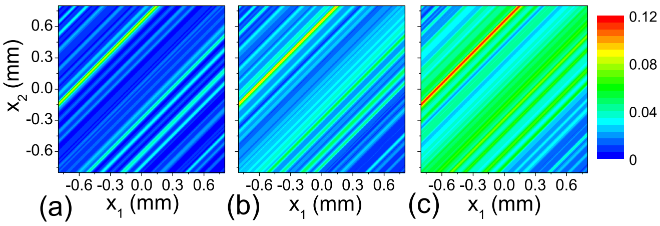

FIG. 5. (Color online) Effect of the imperfect PC fields on the distributions of $\mu_M^{(p)}(x_1,x_2)$ for the random diffusers in configuration (ii) with (a) $\sigma^2 = 0.01$, (b) $\sigma^2 = 0.04$, and (c) $\sigma^2 = 0.09$. Other parameters are the same as in Fig. 4.

and the nonfactorizable features in the correlation patterns can be clearly seen. For small f_c, the correlation speckle spots are elongated along the coordinate subtraction $x_1 - x_2$ because the second diffuser is illuminated with the far-field patterns of the first diffuser. The smaller f_c is, the less information from the first diffuser can be projected onto the same area of the second diffuser. This can be seen from the function $\Theta_p(\upsilon_1,\upsilon_2)$. Therefore, the modified HBT scheme can provide the phase-sensitive IIC speckles.

Finally, let us discuss the possibility of experimental realization of our scheme. The main problem is that imperfect PC fields may have an influence on the intensity-intensity correlations. Assume that the relation between the input and output of a practical PC device at the ξ plane (see Fig. 2) becomes $E_{\text{PC,out}}(\xi) = \alpha[1 + R(\xi)]E^*_{\text{PC,in}}(\xi)$, where a reduced dimensionless random complex function $R(\xi)$ denotes the random fluctuation part of the PC fields. The processes of generating PC fields are assumed to be independent of each other at different ξ, thus $\langle R(\xi)\rangle = 0$ and $\langle R(\xi)R^*(\xi')\rangle = \sigma^2\delta(\xi - \xi')$, where σ^2 is the reduced variance of the random fluctuation part. The smaller the value of σ^2, the higher the quality of the PC fields is [37]. For example, the random fluctuation part in the total PC field takes ~9.1%, ~16.7%, and ~23.1%, respectively, for $\sigma^2 = 0.01$, 0.04, and 0.09, respectively in the below simulations. From the above calculation procedure, similar equations, containing the effect of imperfect PC fields on the IIC patterns, can be obtained. Figure 5 shows the effect of the imperfect PC fields on the normalized phase-sensitive shape function $\mu_M^{(p)}(x_1,x_2)$ for configuration (ii) as an example. It is clear that the visibility of the patterns may decrease as the value of σ^2 increases, but the main characteristic of interference or speckle patterns is still observable even for a considerably large value of σ^2 [see Fig. 5(c)]. There are similar results for configurations (i) and (iii). Therefore, our results are reliable and can be demonstrated even by using the imperfect PC fields of thermal light.

In order to generate the PC fields, one can employ the conventional PC technologies, such as four-wave-mixing processes (e.g., Refs. [38–41]) and stimulated scattering processes (e.g., Refs. [42–45]). The nondegenerate PC light with high fidelity can be also generated by using a Pr^{3+}:Y_2SiO_5 crystal [46]. Alternatively, one may also use digital PC technology [47–49] to provide the high-quality PC light fields. This does not involve nonlinear processes but can generate high-quality PC waves even for a weak and incoherent fluorescence signal [50]. Meanwhile, the input thermal light can also be replaced by pseudothermal light sources [51].

In summary, we have presented the phase-sensitive IIC speckle effect of thermal light in the modified HBT scheme. This scheme is based on introducing the PC light to change the correlations between two optical paths. It is revealed that the phase-sensitive and nonfactorizable features can be seen in modified thermal IIC speckles. Finally, we showed the effect of imperfect PC fields on thermal phase-sensitive IIC speckles, which verifies these observable effects in our modified HBT scheme. This scheme is different from thermal ghost imaging, diffraction [8–10,36,52], and unbalanced interferometer-based schemes [53]. All thermal photons in our case pass through the common sample. Our scheme may also be used to recover the phase information in thermal-like temporal IIC cases [54]. This modified HBT scheme may have important applications in the development of the IIC speckle and imaging technologies of thermal or incoherent light sources.

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