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Experimental Study on Coherence Time of a Light Field with Single Photon Counting *

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The second-order degree of coherence of pseudo-thermal light and coherence time are experimentally studied via the Hanbruy-Brown–Twiss (HBT) scheme. The system consists of two non-photon-number-resolving single-photon-counting modules (SPCMs) operating in the Geiger mode. We investigate the coherence time of the incident beam for different spot sizes on a ground glass and speeds of a rotating ground glass. The corresponding coherence time can be obtained from Gaussian fitting for the measured second-order degree of coherence. The results show that the coherence time of measured pseudo-thermal light depends on the spot sizes and the rotating speeds of the ground glass. The maximum value of the second-order degree of coherence is reduced as the rotating speed decreases. This result can be well explained by the model of mixed thermal and coherent fields with different ratios.

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Photon counting detection, as the most sensitive measurement in optics, has been used to determine the photon statistical properties of light fields since the experiment of intensity correlation (Hanbury-Brown and Twiss, HBT experiment) in 1956.[1] Following the HBT experiment, high-order correlation of a single mode laser was achieved by Arecchi in 1966.[2] Photon antibunching was observed in resonance fluorescence by Kimble in 1977.[3] Nowadays, the HBT scheme has become a standard system to evaluate the single photon source (SPS),[4] which is important in atomic physics, quantum optics and quantum information science.[5,6] Recently, fast, highly efficient single-photon-counting modules (SPCMs) with low dark counts[7,8] have been widely used in quantum optical experiments[9] and ultra-sensitive measurements.[10]

Pseudo-thermal light (PTL) behaves like thermal light with adjustable temporal and spatial coherence, and is widely used in quantum optics experiments. PTL is produced by laser light after passing through a rotating ground glass. Martienssen and Spiller[11] first introduced quasi-thermal light. Using PTL they demonstrated an intensity interference experiment with the HBT configuration,[1] and investigated the role of intensity fluctuations in Young's double-slit experiment. Arecchi[12] later measured the photon number distribution of the field based on the photon counting technique. The results showed that the field has a Gaussian distribution but its coherence time is determined by the transit time of the laser beam passing through the ground glass. Troup and Lyons pointed out that the Poisson distribution of laser light can become a Bose–Einstein distribution after passing through a rotating ground glass. The rotating ground glass can be considered as a system for changing the statistical properties of an incident light beam.[13] Beran and Parrent mentioned that the rotating ground glass can also reduce the spatial coherence of the field.[14] Asakura has shown that the spatial coherence of PTL depends on the illuminated area, the fineness of the glass and the laser mode itself but not on the speed of rotation of the glass.[15] The relationship between the half width of the Gaussian distribution of PTL and the linear velocity of the ground glass and the light spot size on the ground glass was investigated.[16] Due to its easy preparation and manipulation, PTL plays an important role in modern quantum optics experiments, such as ghost imaging,[17−20] coherence studies in holography,[21] and so on. In previous work, we studied the second-order degree of coherence from pulsed to continuous operation and the photon statistical distribution of PTL,[22,23] but did not discuss the coherence time of the field. In this Letter, the coherence time of the is extensively investigated in the case of different spot sizes on the ground glass and speeds of the rotating ground glass based on the non-photon-number-resolving SPCMs. It is shown that the coherence time of measured PTL changes with different spot sizes and rotating speeds of the ground glass. The maximum value of the second-order degree of coherence is re-

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duced as the rotating speed decreases. The result can be well explained by the model of mixed thermal and coherent fields with different ratios.

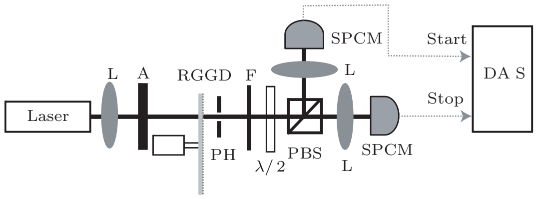

Fig. 1. Experimental setup. L: lens. A: neutral attenuator. RGGD: rotating ground glass disk. PH: pinhole. F: filter. $\lambda/2$: half wave plate. PBS: polarizing beam splitter. SPCM: single-photon-counting module. DAS: data acquisition system.

Figure 1 shows our experimental setup. PTL is produced by sending an attenuated and focused laser beam at 852 nm onto a rotating ground glass disk (RGGD). The beam goes through a pinhole and a filter (F), and is divided into two equal parts by a half wave plate ($\lambda/2$) and a polarizing beam splitter (PBS). The transmitted and reflected beams are focused on two single-photon-counting modules (SPCM-AQR-15, PerkinElmer Optoelectronics). Coincidence of the two channels can be obtained, and the second-order degree of coherence, $g^{(2)}(\tau)$, of the incident light field can be achieved after data normalization.

The effective radius, i.e., the distance between the position of the incident beam on the ground glass and the center of the ground glass, is 2 cm. The rotating speed of the RGGD can be controlled very well. A small pinhole is used to ensure that the output field has a very good spatial coherence.[24] The quantum efficiency of the SPCMs is about 48% at 852 nm and their dark counts are 55 cps and 150 cps, respectively. The dead time of the detector is about 50 ns, which can be avoided with the HBT scheme.[22] The shortest resolution time of the system is limited by the data acquisition card, which is 1 ns. In the experiment, the resolution time of the detection system is fixed at 32 ns, which is much shorter than the coherence time of the field, of the order of microseconds. The count rate of both detectors is 26 kcps.

In order to study the spot size effect on the coherent time, we choose two lenses with different focal lengths, 50 mm and 12.7 mm, respectively. The second-order degree of coherence of PLT versus the delay time is measured when the linear velocity of the rotating ground glass changes. For each experimental parameter, the coherent time can be obtained by Gaussian fitting,

$$g^{(2)}(\tau) = B + A\exp\left(-\frac{\tau^2}{\tau_c^2}\right), \tag{1}$$

where τ is the delay time, τ_c is the coherence time, B is a parameter close to 1,[25] and A is the amplitude of the second order of coherence. According to Eq. (1), we can obtain τ_c versus the linear velocity of the rotating ground glass for the above-mentioned two lenses. The result is shown in Fig. 2. The triangles and dots in Fig. 2 correspond to $f = 50$ mm and $f = 12.7$ mm, respectively. It clearly shows that at the same linear velocity the coherence time is short for the shorter focal length, which corresponds to the smaller beam spot size on the RGGD.

In Ref. [16], the half-width at half-height of the field-power spectrum of PTL is given by

$$\Delta\omega_{\frac{1}{2}} = 2\ln 2v\left(\frac{k^2\sigma^2}{f^2} + \frac{1}{4\sigma^2}\right)^{\frac{1}{2}}, \tag{2}$$

where v is the linear velocity of the rotating ground glass, f is the focal length of lens, k is the wave vector, and σ is the radius of the incident laser beam. According to Eq. (2), the coherence time of PTL can be represented as,

$$\tau_c = \frac{1}{v}\left(\frac{k^2\sigma^2}{f^2} + \frac{1}{4\sigma^2}\right)^{-\frac{1}{2}}. \tag{3}$$

The solid line in Fig. 2 is the theoretical result according to Eq. (3). It shows that the experimental results are in accordance with theory. It is found that PTL with controllable coherence time can be prepared by adjusting the linear velocity of the RGGD and the spot size of incident beam. This coherence controllable light is very useful not only in quantum optics and quantum information science, but also in studying light–matter interactions.[26]

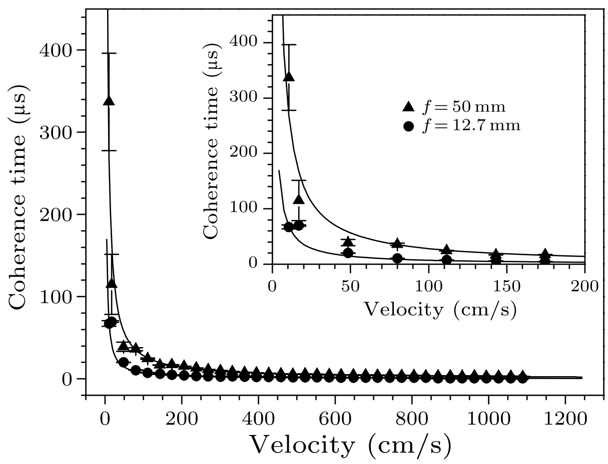

Fig. 2. Coherence time of pseudo thermal field versus linear velocity of the ground glass for different focal lengths. The insert shows the results in the range from 0 to 200 cm/s. The triangles and dots are the experimental results corresponding to $f = 50$ mm and $f = 12.7$ mm, respectively. The lines are obtained from Eq. (3) and σ is 240 μm.

We have seen that the maximum of the measured second-order degree of coherence of PTL decreases as the speed of the rotating ground glass reduces, as shown in Fig. 3. The grey lines in Figs. 3(a), 3(b), 3(c) and 3(d) correspond to a linear velocity of 4.2 cm/s, 10.5 cm/s, 174.5 cm/s and 679 cm/s, respectively. We use a lens with a focal length of 12.7 mm. The black lines in Figs. 3(b), 3(c) and 3(d) are the Gaussian fittings, and in Fig. 3(a) we use the adjacent average smoothing (5 points). It shows that the maximum value of the second-order degree of coherence increases and coherence time decreases as the speed of the rotating ground glass increases.

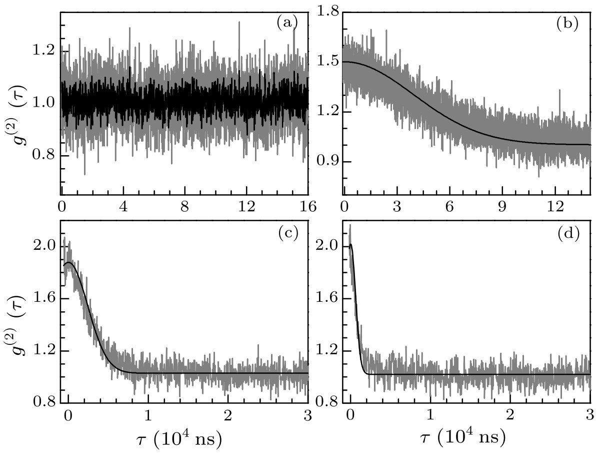

Fig. 3. Second-order degree of coherence of PTL versus linear velocity of the ground glass when the focal length of the lens is 12.7 mm. From (a) to (d), the linear velocity is 4.2 cm/s, 10.5 cm/s, 174.5 cm/s and 679 cm/s, respectively.

These results can be explained as follows: PTL generated by the rotating ground glass is actually not a pure thermal state, but certainly a mixture of a thermal state and a coherent state. The mixture ratio is determined by the status of the rotating ground glass, the incident laser light itself and the background environment. This ratio varies with the speed of the ground glass. In the case of high speed of the rotating ground glass, the proportion of coherent light is low because the randomness of the phase of the incident beam caused by the moving particles of the RGGD becomes stronger. The second-order degree of coherence of the mixed field is[24]

$$g^{(2)}(\tau) = 1 + \Big(\frac{s}{1+s}\Big)^2 \exp\Big(-\frac{\tau^2}{\tau_c^2}\Big) + \frac{2s}{(1+s)^2} \exp\Big(-\frac{\tau^2}{2\tau_c^2}\Big), \tag{4}$$

where s is the power ratio of thermal light to coherent light, and τ_c is the coherence time of the mixed fields. We only discuss the temporal coherence, and the impact of spatial coherence is not considered. Figure 4 shows the results when considering the coherence time which changes along with the speed of the ground glass, while the coherence time of those parts of coherent light is unchanged. The solid line is the calculated result when the field is an ideal thermal light with a coherence time of 1.4 µs. The dashed, dotted and dot-dashed lines correspond to 2.5, 1 and 0.25 of the power ratios and 2 µs, 5 µs, 10 µs of τ_c, respectively. We can see clearly that the mixed model in excellent agreement with the experimental results. The second-order degree of coherence becomes larger as the thermal light dominates the output beam.

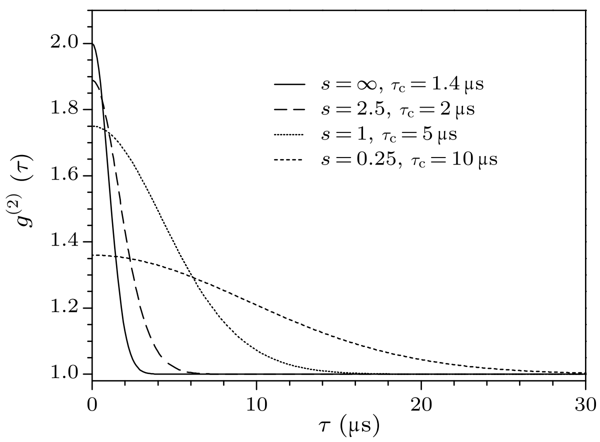

Fig. 4. Second-order degree of coherence versus delay time according to the mixed model of thermal and coherent fields. Here s is the power ratio of thermal light to coherent light, and τ_c is the coherence time of the mixed fields.

In conclusion, the second-order degree of coherence of PTL is investigated via the HBT scheme when the spot sizes of the incident beam on the ground glass and the linear velocity of the rotating ground glass are varied. The coherence time is achieved from the results of Gaussian fitting. The results show that the coherence time of measured PTL depends on the spot sizes and the rotating speeds of the RGGD. The maximum second-order degree of coherence is reduced as the rotating speed decreases. This result can be well explained by the model of mixed thermal and coherent fields with different ratios. The method of determining the coherence time of a light field by means of non-photon-number-resolving detectors is direct, reliable and easy, and can be used in the measurement of spatial coherence,[27] photon correlation spectroscopy,[28] and so on.

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