Spatial photon-coincidence measurements in a multiple scattering medium

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Spatial photon correlations induced by multiple scattering of light are directly measured for light sources with different photon statistics. We resolve spatially multiple scattered photons and demonstrate the angular and temporal dependence of the spatial photon correlation function. The data are found to be in excellent agreement with the continuous mode quantum theory of multiple scattering of light. The measurements form the basis for further studies of quantum phenomena in multiple scattering random media such as quantum interference and quantum entanglement of photons.

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Light that propagates through a randomly disordered medium is multiply scattered and forms thereby a volume speckle pattern [1]. After averaging over configurations of disorder interference effects generally disappear and the light transport can be described by diffusion theory. In this case the different spatial paths through the medium are uncorrelated. In strongly scattering media deviations from diffusive transport occur giving rise to mesoscopic intensity correlations or Anderson localization. While these effects can be described by classical optics, quantum properties can be observed in the photon statistics and photon correlations of multiple scattered light [2–8]. Recently, spatial quantum correlations induced by multiple scattering of squeezed light were observed [6]. The spatial quantum correlation function was obtained from total transmission quantum noise measurements by averaging over all spatial directions.

We present the first *direct* spatial photon correlation measurement of multiply scattered light, which is the spatial analogue of the Hanbury Brown and Twiss experiment [9] generalized to a multiple scattering setting. For various photon distributions of the light source we resolve multiply scattered photons that propagate along different spatial directions. The spatial photon correlation function is found to be dependent on the second order coherence function of the light source and on classical intensity correlations induced by the multiple scattering medium. Our experiments confirm the quantum theory of multiple scattering in the time domain and pave the way to study recently predicted quantum interference phenomena and quantum entanglement of multiply scattered photons [5, 7].

The spatial photon correlation function between two directions b and b', having an incident light wave in direction a (see Fig 1), is defined by

$$\overline{C^{Q}_{abab'}(\tau)} = \frac{\overline{\langle : \hat{n}_{ab}(t)\hat{n}_{ab'}(t+\tau) : \rangle}}{\overline{\langle \hat{n}_{ab}(t)\rangle} \times \overline{\langle \hat{n}_{ab'}(t)\rangle}}. \qquad (1)$$

$\langle : \cdots : \rangle$ is the quantum mechanical expectation value of normally ordered operators [10] and $\hat{n}_{ab}(t)$ is the photon operator. The horizontal bars represent the ensemble average over different realizations of disorder. We further consider a stationary light source whose statistical fluctuations do not change in time. The spatial correlation function therefore only depends on the time difference τ of the measurement between b and b' [11]. The time dependent spatial photon correlation function using the continuous mode quantum theory of multiple scattering is found to be

$$\overline{C^{Q}_{abab'}(\tau)} = \frac{\langle : \hat{n}_{a}(t)\hat{n}_{a}(t+\tau) : \rangle}{\langle \hat{n}_{a}(t)\rangle^{2}} \times \overline{C^{C}_{abab'}}. \qquad (2)$$

The first term on the right hand side represents the second order coherence function of the light source while the latter factor $\overline{C^{C}_{abab'}} = \overline{\langle \hat{n}_{ab}\rangle \langle \hat{n}_{ab'}\rangle} / \left(\overline{\langle \hat{n}_{ab}\rangle} \times \overline{\langle \hat{n}_{ab'}\rangle}\right)$ is due to classical intensity correlations [1]. For the selected case of a thermal light source we have [11]

$$\overline{C^{Q}_{abab'}(\tau)} = \left[1 + \exp\left(-\pi(\tau/\tau_c)^2\right)\right] \times \overline{C^{C}_{abab'}}, \qquad (3)$$

with τ_c being the coherence time. On the contrary, photons of a coherent light source are uncorrelated and the spatial photon correlation function equals the classical intensity correlations.

The experimental setup is illustrated in Fig. 1. As a light source we use a continuous wave titanium sapphire laser ($\lambda = 780\,\mathrm{nm}$) that is focused onto a ground glass plate. Super-Poissonian photon statistics is obtained by a superposing coherent beams with random amplitudes

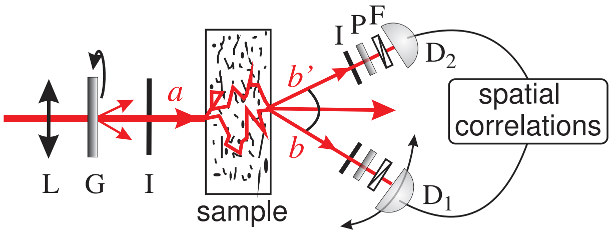

Fig. 1. (color online) Sketch of the experimental setup. L: lens, G: ground glass plate, I: iris, P: polarizer, F: 10 nm interference filter, Θ: angle between detector D$_1$ and D$_2$; a: incident light channel; b, b': exit light channels.

and phases by slowly rotating the ground glass plate and collecting a fraction of the transmitted light using an iris [12]. The collimated light beam is then directed onto the front surface of a multiple scattering medium which consists of TiO$_2$ nano-particles (thickness $L = 6.3 \pm 0.2\,\mu$m, transport mean free path $\ell = 0.9 \pm 0.1\,\mu$m [13]). Two avalanche photo diodes (APDs) are positioned behind the sample to record multiply scattered photons at different spatial directions. Detector D$_1$ can be displaced to vary the angle Θ between both detectors. We avoid the contribution from ballistic propagation of light through the multiple scattering medium by only collecting light polarized perpendicular to the incident light polarization. The apertures in front of the APDs ensure light collection from only a single speckle spot. Each detector records $\hat{n}$ photons within a time interval $\Delta t = 266\mu$s. The expectation value $\langle \hat{n}(t)\rangle$ as well as the variance of the photon fluctuations $\Delta n^2(t) = \langle \hat{n}^2(t)\rangle - \langle \hat{n}(t)\rangle^2$ are obtained by counting photons in many time intervals Δt. For a stationary light source only relative time differences τ influence the measurements and the time argument t can be neglected. We measure the spatial photon correlation function (Eq. (1)) between two directions by recording simultaneously the ensemble averaged number of photons in each direction ($\overline{\langle \hat{n}_{ab}\rangle}$, $\overline{\langle \hat{n}_{ab'}\rangle}$) as well as the ensemble averaged photon coincidences between both directions ($\overline{\langle \hat{n}_{ab}(0)\hat{n}_{ab'}(\tau)\rangle}$). The ensemble average is achieved after repeating the measurement at $N = 200$ different sample positions and thereby probing different realizations of disorder. The experimental configuration allows us to independently measure classical intensity correlations $\overline{C^C_{abab'}}$ (c.f. Eq. (2)). For this purpose we record the ensemble averaged number of photons $\overline{\langle \hat{n}_{ab}\rangle}$ on each detector and the joint ensemble average $\overline{\langle \hat{n}_{ab}\rangle\langle \hat{n}_{ab'}\rangle}$ on both detectors.

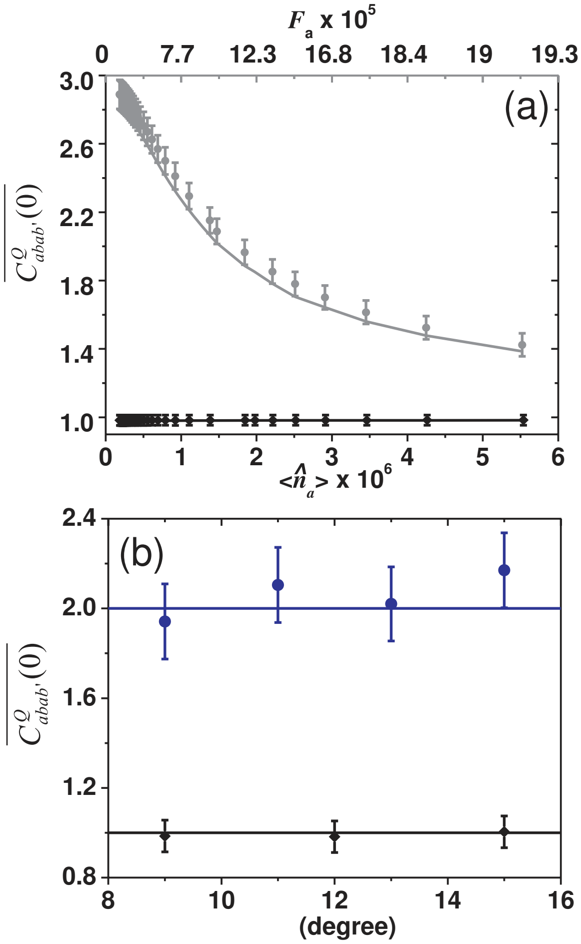

Fig. 2. (color online) (a) Photon correlation function $\overline{C^Q_{abab'}(0)}$ depending on $\langle \hat{n}_a\rangle$ and F_a that is measured by slowly rotating the ground glass plate of the light source (gray circles). Measurements for a coherent state (black squares) show $\overline{C^Q_{abab'}(0)}$ independent of $\langle \hat{n}_a\rangle$. The error bars are determined by the uncertainties in F_a and the theoretical predictions contain no free fitting parameters (lines). (b) Angle dependence of $\overline{C^Q_{abab'}(0)}$ for a coherent light source (black squares) and a Gaussian radiation source (blue circles). Detector D$_1$ is rotated behind the sample to change Θ. The straight lines are theoretical predictions assuming that the classical intensity correlations equal to unity.

First we investigate the spatial photon correlation function depending on the number of photons $\langle \hat{n}_a\rangle$ and variance in the photon fluctuations Δn_a^2 of the light source incident on the sample. Fig. 2(a) shows the ensemble averaged spatial photon correlation function that is induced by multiple scattering of light as a function of the Fano factor $F_a \equiv \Delta n_a^2 / \langle \hat{n}_a\rangle$. For light sources with super-Poissonian probability distributions ($F_a > 1$) we measure an increase of $\overline{C^Q_{abab'}(0)}$ with decreasing number of incident photons. The maximum value in the spatial photon correlations that we measure is 2.9. We observe that $\overline{C^Q_{abab'}(0)}$ is independent of the incident number of photons for a coherent light source, as obtained by removing the ground glass plate (c.f. Fig. 2(a)). The experimental measurement of the spatial photon correlation function is found to be in very good agreement with theory without any adjustable fitting parameters. The slightly smaller predicted value of $\overline{C^Q_{abab'}(0)}$ for $F_a > 1$ can be explained by variations in the rotation speed of the ground glass plate over time, which influence the

Fano factor.

In the diffusive regime, spatial photon correlations are predicted to be infinite in range, i.e. to be independent of the exit direction. Fig. 2(b) plots the spatial photon correlation function as a function of the angle Θ between the detector D_1 and D_2 for a coherent and for a Gaussian radiation source. We generate a Gaussian radiation source that reflects the characteristics of thermal light ($F_a \approx \langle \hat{n}_a \rangle$) [12] by changing the rotation speed of the glass plate and Δt, respectively. The error bars in $\overline{C^{Q}_{abab'}}(0)$ arise mainly from uncertainties in the classical intensity correlations caused by a finite number of disorder realizations contributing to the ensemble average. In good agreement with theory we do not observe a dependence of the photon correlations on the angle between the direction of multiple scattered light which confirms that the spatial photon correlation function is infinite in range.

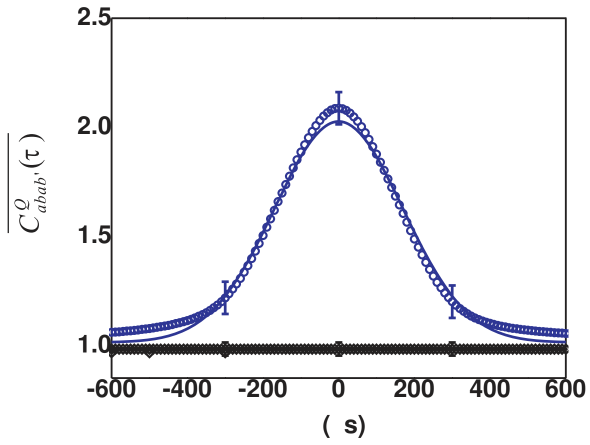

Fig. 3. (color online) Measured temporal dependence of the spatial photon correlation function for a Gaussian radiation source (blue circles) and a coherent light source (black squares), plotted with representative selected error bars. The straight blue line is a fit to the data with the coherence time as a free parameter. The black line represents the theory for a coherent light source.

Finally the temporal dependence of the spatial photon correlations is studied for a Gaussian radiation source, shown in Fig. 3. For this purpose we induce a relative time difference τ between detector D_1 and D_2. A clear decay of the spatial correlation function is observed. Fitting the experimental results with theory (Eq. (3)), the coherence time of the Gaussian radiation source is estimated to be $\tau_c = 750\,\mu$s. The coherence time describes the average time interval between phase distortion fluctuations of the light source. Only coherence times of the light source can be resolved that are larger than Δt, i.e., the experimentally measured photon statistics do not contain information about photon fluctuations on shorter timescales. As $\tau_c > \Delta t$ we resolve the coherence time of our Gaussian radiation source. For comparison, the temporal dependence of the spatial photon correlation function is investigated for a coherent light source (Fig. 3). Coherent light exhibits long coherence times and the photons are uncorrelated. We find a very good agreement between experiment and theory, which predicts that the spatial photon correlation function is independent of τ and equals unity.

In conclusion, we demonstrated experimentally the first direct measurement of spatial photon correlations induced by multiple scattering of light. Multiple scattered photons were spatially resolved and it has been verified that in the diffusive regime the correlation function is infinite in range. The correlations were found to be dependent on the photon statistics of the incident light source and our experimental results are in excellent agreement with the continuous mode quantum theory of multiple scattering. Very recently, it has been predicted that quantum interference may survive multiple scattering in disordered arrays of coupled waveguides [7]. The presented method will allow studying similar effects experimentally in three dimensional disordered media.

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