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Coherent imaging of a pure phase object with classical incoherent light

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Ghost imaging provides coherent imaging with incoherent light by exploiting the spatial correlation between two incoherent beams created by, e.g., parametric down conversion (PDC). Each beam is sent through a distinct imaging system; the test and the reference arm. In the test arm an object is placed, while the reference arm contains only reference optics. Since the object is illuminated with spatially incoherent light no phase sensitive information about the object – such as its diffraction pattern – can be extracted by measuring only on the test arm. However, because of the mutual spatial correlation between the two beams, the diffraction pattern may be reconstructed by measuring the spatial cross-correlation between the beams. In other words, despite the beams being incoherent, the spatial coherence *between them* allows to perform coherent imaging: the ghost imaging scheme is therefore capable of doing *coherent imaging with incoherent light*. A particular case is when the object only alters the amplitude of the light, e.g., a Young's double slit: In this case, e.g., the Hanbury-Brown–Twiss (HBT) scheme can be used to measure the autocorrelation in the far zone of the test arm, and thereby extract the diffraction pattern even when using spatially incoherent light. However, for a general object, the HBT scheme cannot be used to extract information about the diffraction pattern when using incoherent light. It is therefore interesting to look beyond the case of an amplitude-only object. Here, we use a ghost imaging scheme to observe the diffraction pattern of a *pure phase object* (i.e., it only alters phase information).

Initially ghost imaging was believed to require spatial quantum entanglement between the arms. However, our group has shown that basically all features of quantum ghost imaging can be mimicked by using classically correlated beams created by dividing a spatially incoherent pseudo-thermal speckle beam on a beam splitter (BS) [1]. The two outgoing beams are still incoherent, but since they are classical copies of each other they have a *high mutual spatial coherence*. We showed that *both* the quantum and the classical ghost imaging scheme provide *coherent imaging using incoherent light*: they are both able to reconstruct the diffraction pattern of any object altering amplitude and/or phase. In Ref. [1] we experimentally confirmed this prediction in the case of an amplitude object. Ref. [2] experimentally measured the ghost diffraction pattern of a pure phase object using PDC entangled photons, but (falsely) stated that the classical ghost imaging scheme used by us in Ref. [1] only worked because the thermal light was made spatially coherent. This statement suggested that coherent imaging with spatially incoherent light is not possible with a classical ghost imaging scheme, and that quantum entanglement is needed to observe the ghost diffraction pattern of a pure phase object.

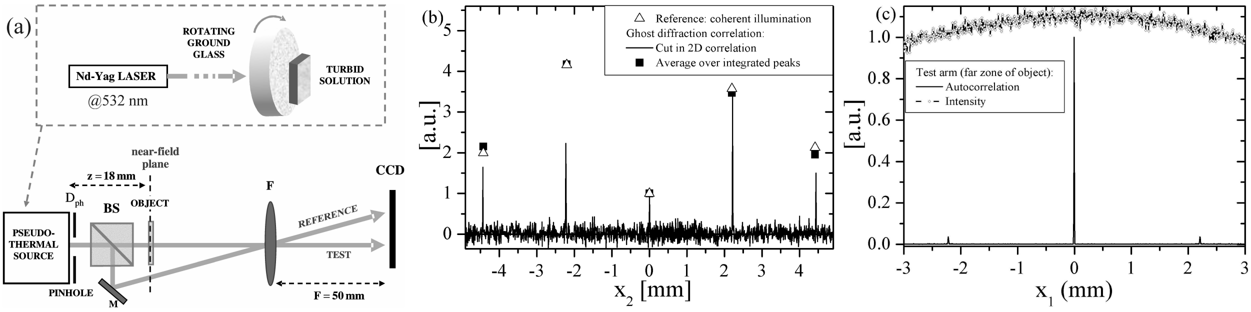

Fig. 1 (a) Experimental setup. (b) Ghost diffraction pattern vs. the reference arm pixel position x_2 while fixing the test arm pixel position x_1. (c) Test arm autocorrelation and average intensity. 18,000 frames were used for the averages.

To disprove this, we performed the experiment of Fig. 1a. A pseudo-thermal source created a speckle beam with millions of speckles (2 µm size, ~5 mm beam size). When split on the BS two spatially highly incoherent beams were created with a mutual classical correlation. These were used to record the ghost diffraction pattern of the pure phase object (a transmission grating beam splitter) in the test arm. A 1D cut of the cross-correlation (Fig. 1b) corresponded well to the reference peaks of the object diffraction pattern (obtained by measuring the far-zone intensity with coherent illumination of the object). Due to the object's sharp diffraction peaks, better results were obtained by "integrating" over the CCD pixels around the peaks. Fig. 1c verifies that no information about the diffraction pattern is present in the test arm, neither in the far zone intensity distribution nor in the autocorrelation (a HBT type of measurement). We checked that when increasing the spatial coherence the diffraction pattern disappeared from the cross-correlation, while it appeared in the autocorrelation. Indeed, the cross-correlation contains information about the phase object *only when the light is spatially incoherent*. Thus, the ghost imaging scheme – be it quantum or classical – and the HBT scheme are *complementary*. Generally, the more the light is coherent in the HBT scheme the better the information is reconstructed. Conversely, the more the light is incoherent in the ghost imaging scheme the better the information is reconstructed.

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