Abstract- In a recent paper, a scheme of ghost imaging with two EPR states, AB and CD, was considered, with photons A and C being coupled by a 50/50 non-polarizing beam splitter. In the present paper, a modification of the scheme is considered wherein, instead of entangled photons, two-photon states of thermal light are utilized. Photon A passes through the object plane, and photon B passes through the image plane. In the scheme, the image-forming correlation between photons A and B is observed in the joint detection of photons B and D.

Key Words: Ghost imaging, Two-photon state, Thermal light.

1. INTRODUCTION

In quantum mechanics, the spatial correlations between the particles are defined by two-particle states. The spatial correlation between the particles in the points with coordinates \( \bar{x}_1 \) and \( \bar{x}_2 \) is given by the delta function, \( \delta(\bar{x}_1 - \bar{x}_2) \). One can combine two-particle states into the chain. Consider the chain of two-particle states between four particles. The spatial correlations between the particles in the chain can be described by the combination of the delta functions, \( \delta(\bar{x}_1 - \bar{x}_2)\delta(\bar{x}_3 - \bar{x}_4) \). The chain of the particles allows to measure the spatial correlation between the first and second particles, \( \delta(\bar{x}_1 - \bar{x}_2) \), through the spatial correlation between the first and fourth particles, \( \delta(\bar{x}_1 - \bar{x}_4) \).

A scheme with two EPR states was considered in [1-3]. EPR states, AB and CD, form the chain through the coupling of photons A and C at a 50/50 non-polarizing beam splitter. In the scheme, the correlation between photons A and B is measured through the correlation between photons B and D. The scheme is similar to the scheme for entanglement swapping. Unlike the standard scheme for entanglement swapping used for teleportation of a Bell state, the scheme [1-3] is intended for teleportation of the phase between the photons.

In [4], the scheme with two EPR states was applied to ghost imaging. In the scheme, the image-forming correlation between photons A and B is observed in the joint detection of photons B and D. In the present paper, a modification of the scheme [4] will be considered wherein, instead of entangled photons, two-photon states of thermal light are utilized.

2. GHOST IMAGING WITH THERMAL LIGHT

Ghost imaging is a quantum technique with the use of non-local two-photon states [5]; see also recent works [6-8]. The type-one ghost imaging utilizes entangled photons, and the type-two ghost imaging utilizes thermal light. The scheme of the type-two ghost imaging with thermal light is depicted in Fig. 1. The thermal radiation of a chaotic source is split in two spatial modes by a 50/50 non-polarizing beam splitter. The reflected light illuminates an aperture (object). The photons passing through the object are collected by a convex lens (not shown in the figure) and counted by a bucket detector \( D_1 \). The transmitted light goes directly from the source to detector \( D_2 \), scanning in the transverse plane. The outputs of both detectors are sent to a coincidence circuit for counting the joint-detection between \( D_1 \) and \( D_2 \). A ghost image of the object is observed in the joint-detection between \( D_1 \) and \( D_2 \) during the scanning of detector \( D_2 \) in the transverse direction in the plane \( z_1 = z_2 \), where \( z_1 \) is the distance from the source to the object, \( z_2 \) is the distance from the source to the input tip of the fibre of detector \( D_2 \), being scanned in the transverse plane. The single detectors counting rates of \( D_1 \) and \( D_2 \) are both monitored to be constants in the object plane and in the image plane as well as in time.

Fig. 1: Scheme of ghost imaging with thermal light. BS: beam splitter, D: detector, CC: coincidence circuit.

The partial correlation of thermal light is given by

\[
G^{(2)}(\tilde{\rho}_1, \tilde{\rho}_2) \sim 1 + \delta(\tilde{\rho}_1 - \tilde{\rho}_2) \quad (1)
\]

where \( \tilde{\rho} \) is the transverse coordinate of the detector. The joint detection counting rate is given by

\[
R_{\text{det}}(\tilde{\rho}_1) \sim \int d\tilde{\rho}_2 |A\tilde{\rho}_1| \otimes [1 + \delta(\tilde{\rho}_1 - \tilde{\rho}_2)] \sim \text{const} + |A\tilde{\rho}_1|^2. \quad (2)
\]

This indicates an image of the object aperture function by means of the joint-detection events between distant detectors \( D_1 \) and \( D_2 \) while scanning \( D_2 \) in the image plane, with the maximum visibility 50%.

3. SCHEME OF THE ARRANGEMENT

Consider the scheme of ghost imaging with two two-photon states of thermal light, see the scheme of the
arrangement in Fig. 2. The thermal radiation of two sources is split by 50/50 non-polarizing beam splitters $BS_1$ and $BS_2$ in two-photon states $AB$ and $CD$ respectively. Photons $A$ and $C$ are coupled by a 50/50 non-polarizing beam splitter $BS_3$. Two-photon states $BA$, $AC$, $CD$ form the chain, with the correlation $BD$ being the combination of $BA$, $AC$, $CD$.

Photon $A$ illuminates an aperture (object) and then is collected by a convex lens (not shown in the figure). Beam splitter $BS_1$ is placed at the focus of the lens. Photons $B$, $C$, $D$ go freely. Photon $B$ is captured by a point-like detector $D_2$, scanning along the transverse direction. Photon $D$ is captured by a bucket detector $D_1$ kept in a fixed position. The outputs of both detectors are sent to a coincidence circuit for counting the joint-detection events.

![Image of scheme](image.png)

Fig. 2: Scheme of the arrangement. BS: beam splitter, D: detector, CC: coincidence circuit.

In the scheme, the transverse wave vector of photon $A$ is changed by the aperture (object) that gives rise to the change of the transverse wave vector of photon $B$ defined by the transverse momentum correlation, $[1 + \delta(k_x A + k_x B)]$. Accordingly, the function $[1 + \delta(\hat{\rho}_A - \hat{\rho}_B)]$ defines the transverse spatial correlation of photons $A$ and $B$. The object plane is at the place of the aperture, and the image plane is at the place of the fibre tip of detector $D_2$, scanning along the transverse direction. The distance from beam splitter $BS_1$ to the object plane and the distance from beam splitter $BS_1$ to the image plane are the same.

The transverse spatial correlation of photons $C$ and $D$ are defined by the function $[1 + \delta(\hat{\rho}_C - \hat{\rho}_D)]$. The transverse spatial correlation of independent photons $A$ and $C$ coupled at beam splitter $BS_3$ are defined by the function $[1 + \delta(\hat{\rho}_A - \hat{\rho}_C)]$. In effect, the transverse spatial correlation of photons $B$ and $D$ are defined by the function $[1 + \delta(\hat{\rho}_B - \hat{\rho}_D)][1 + \delta(\hat{\rho}_A - \hat{\rho}_C)][1 + \delta(\hat{\rho}_C - \hat{\rho}_D)]$. The correlation of photons $B$ and $D$ includes the image-forming correlation between photons $A$ and $B$. Therefore, a ghost image of the object may be observed in the joint-detection events between detectors $D_1$ and $D_2$ counting photons $D$ and $B$ respectively, during the scanning of detector $D_2$. The maximum visibility of each correlation $BA$, $AC$, $CD$ is 50%. Therefore, the maximum visibility in the joint-detection events $BD$ is 12.5%. The ghost imaging requires the following distances to be of the same length: detector $D_2$ to beam splitter $BS_1$, beam splitter $BS_1$ to beam splitters $BS_3$, beam splitter $BS_3$ to beam splitters $BS_2$, beam splitters $BS_2$ to detector $D_1$.

4. CONCLUSION

We have considered a scheme of ghost imaging with two two-photon states of thermal light, $AB$ and $CD$, with photons $A$ and $C$ being coupled by a 50/50 non-polarizing beam splitter. Two-photon states $BA$, $AC$, $CD$ form the chain wherein the correlations $BA$, $AC$, $CD$ can be combined in the correlation $BD$. Photon $A$ passes through the object plane, and photon $B$ passes through the image plane. Due to the combination of the correlations $BA$, $AC$, $CD$ the image-forming correlation between photons $A$ and $B$ is observed in the joint detection of photons $B$ and $D$, with the maximum visibility 12.5%.

REFERENCES