Direct and ghost interference in double-slit experiments with coincidence measurements

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(Received 10 November 1995; revised manuscript received 9 May 1996)

The transverse spatial properties of the twin light beams of the down-conversion have been recently investigated in experiments using double-slit and coincidence measurements. Fringes are obtained, with a controlled degree of visibility, placing the slits in the signal beam and scanning the signal detector [*direct* interference—Phys. Rev. A **49**, 4176 (1994)] and also, for the degenerated type II down-conversion, with slits in the signal beam and scanning the idler detector [*ghost* interference—Phys. Rev. Lett. **74**, 3600 (1995)]. The idea of a ghost source is used to discuss the direct interference experiment. Using a nondegenerated type I down-conversion, experimental results are obtained showing that the visibility of the ghost interference patterns can be controlled by the ghost source size, analogously as it can be done for a real light source. [S1050-2947(96)01510-7]

PACS number(s): 42.50.Dv

Correlation properties between signal and idler photons of the down-conversion that have been investigated in several experiments over the last ten years, are now being extended to explore the transverse spatial entanglement of the twin photons [1–3]. Transverse entanglements were observed in double-slit experiments [1,3], detecting interference patterns with coincidence measurements. In one of these experiments [1] the double slit was inserted in the signal beam and the fringes were observed in the signal beam through coincidence measurements. These fringes were observed in a configuration where *intensity* fringes could not be observed. The visibility of the coincidence fringes was shown to depend on the idler detection area. In another experiment [3] the double slit was also inserted in the signal beam but the fringes were observed scanning the idler detector and performing coincidence measurements. This effect was explained as if the signal detector behaved as a ghost source. The correlations between signal and idler photons transverse momenta were used to draw this analogy.

In this paper, the idea of ghost interference introduced by Ref. [3] is used to interpret the results obtained by Ref. [1], as if it was produced by a ghost source with variable size and consequently a variable coherence area. This idea explains quantitatively the extinction of the coincidence visibility by the increase of the idler detector diameter, under certain conditions. Experimental results show ghost interference for the nondegenerated type I phase-matching down-conversion. The visibility of these interference patterns depends on the degree of spatial coherence of the imaginary source at the slits. This degree of coherence can be described by classical equations [4].

The ideas presented in Ref. [3] are extended to the case of the nondegenerated down-conversion. In this case the ghost interference oscillatory patterns have an effective wave number determined by the distances between crystal to slits in the signal beam and crystal to idler detector. However, this theory is not enough to explain all the features observed, once it is not able to predict the visibilities of the patterns.

For the degenerated case it was shown [3] that the coincidence rate is proportional to

$$R_c \propto P_{12} = |\epsilon|^2 |e^{ikr_A + i\phi_A} + e^{ikr_B + i\phi_B}|^2 \propto 1 + \cos[k(r_A - r_B)], \tag{1}$$

where $r_A = r_{A1} + r_{A2}$, $r_B = r_{B1} + r_{B2}$, ϕ_A, and ϕ_B are phases due to the pump at points A, B in the crystal (ϕ_A was considered equal to ϕ_B for simplicity), k is the degenerated wave number, ϵ is a constant factor dependent on the pump and the nonlinearity of the crystal, r_{A1} is the path from a point A in the crystal to the signal detector passing through one slit, r_{B1} is the path from a point B in the crystal to the signal detector passing through the other slit, r_{A2} is the path from a point A in the crystal to the idler detector, and r_{B2} is the path from a point B in the crystal to the idler detector. This situation is illustrated by Fig. 5 in Ref. [3].

In a similar reasoning it is simple to show that for the nondegenerated case, with signal and idler wave numbers k_s and k_i, respectively, the coincidence rate is given by

$$R_c \propto P_{12} = |\epsilon|^2 |e^{(ik_i r_{A2} + ik_s r_{A1}) + i\phi_A} + e^{(ik_i r_{B2} + ik_s r_{B1}) + i\phi_B}|^2$$
$$\propto 1 + \cos[k_{eff}(r_{A_F} - r_{B_F}) + k_s(r_{D1} - r_{C1}) + \phi], \tag{2}$$

where

$$k_{eff} = k_s \left(\frac{z_0}{z_2}\right) + k_i \left(1 - \frac{z_0}{z_2}\right), \tag{3}$$

z_0 is the distance between crystal and slits and $z_2 = z_0 + r_{di}$ with r_{di} being the distance between crystal and idler detector. r_{A_F} and r_{B_F} are the paths from points A and B in the crystal to slits C and D. r_{D1} and r_{C1} are the paths from slits C and D to the signal detector, such that $r_{A1} = r_{A_F} + r_{C1}$ and $r_{B1} = r_{B_F} + r_{D1}$. $\phi = \phi_B - \phi_A$ is a constant phase.

The term *direct* interference, is used here for the case in which the coincidence fringes are observed scanning the

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TABLE I. Comparison between measured direct visibilities and ghost predictions. All dimensions in mm.

Distance crystal slits	Distance source slits	Source dimension	μ_E(ghost) uniform	μ_E(ghost) Gaussian	μ_E measure
295	795	0.6	0.98	0.96	0.57
80	580	0.6	0.97	0.93	0.44
35	535	0.6	0.96	0.91	0.52
20	520	0.6	0.96	0.91	0.46
20	520	1.8	0.65	0.42	0.13
20	520	3.6	0.16	0.03	0.09

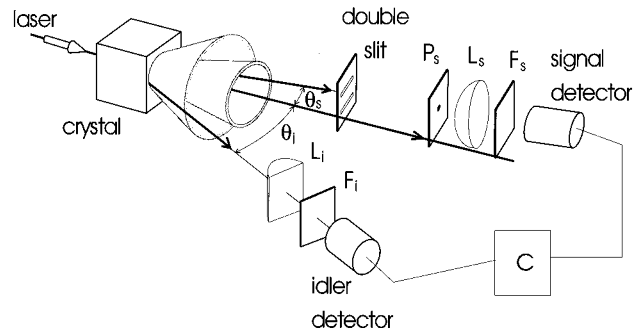

FIG. 1. Outline of the experimental setup. L_i and L_s are lenses. F_i and F_s are optical filters.

same beam where the double slit is placed, to distinguish it from ghost interference, where the fringes are observed in the conjugated beam with no slits.

In the picture provided to explain ghost interference in Ref. [3], one detector works as if it was the light source for the experiment. This explains the *width* of the coincidence patterns. This idea is applied here to discuss the coincidence patterns visibilities of direct and ghost interferences. For the experimental setup described in Ref. [1], the detector working as a source should be the idler detector, because the fringes were observed in the signal beam. The source size, in this case, should be determined by the idler detector pinhole diameter, which restricts the detection area, and can be varied. This picture shows immediately that the coincidence interference can be destroyed, with the increase of the ghost source size. In the ghost terminology, the ghost coherence area at the slits plane was decreased with the increase of the ghost source size so that in the case of the nearly zero visibility, the ghost transverse coherence length at the slits plane was nearly equal to the distance between slits. This is a direct analogy to what happens with real light sources. The prediction for real light sources, including down-converted light, is known [5].

Table I shows a comparison between the data obtained in Ref. [1] and the prediction given by the above analogy, of the dependence μ_E versus distance, using classical equations for a second-order visibility—and not for a fourth-order or coincidence visibility, because the theory is not yet available in the literature. They consider uniform and Gaussian ghost sources (see, for example, Eqs. (8) and (9) of Ref. [5]). This could be interpreted, in this case, as a detector with uniform and Gaussian spatial sensitivities. Some predicted visibilities are greater than 90% while data presented visibilities of the order of 50% maximum. However, they show clearly that this analogy predicts the extinction of the visibility when the idler pinhole diameter, or ghost source size, is increased. In fact, high visibilities are hard to achieve depending on the experimental conditions. Finite slit width can be a factor decreasing visibilities in double-slit experiments [5,6]. Step sizes were used to obtain the fringes such that no appreciable change in the visibility is produced with smaller steps.

The idea of a ghost source was used to predict the extinction of the interference in *direct* coincidence patterns detection, suggesting that the entangled coherence properties

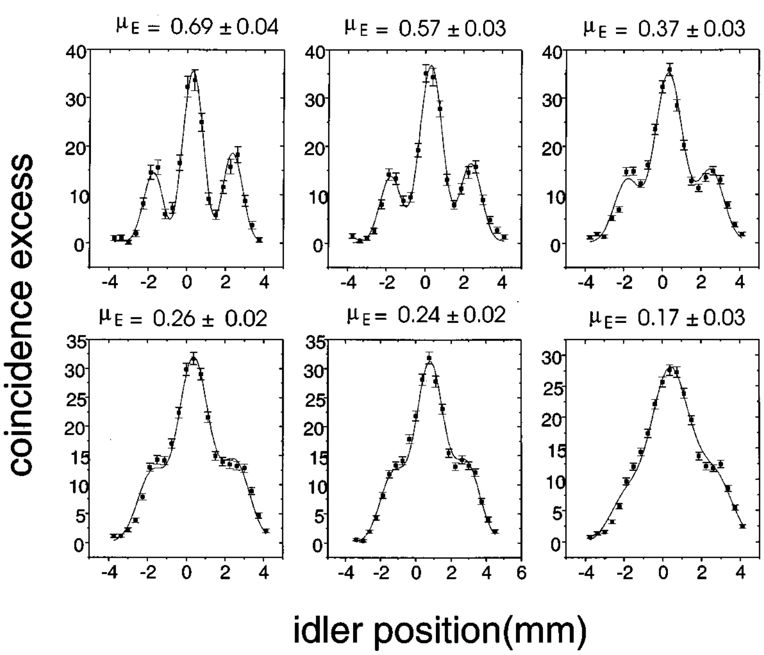

FIG. 2. *Ghost* Interference patterns. μ_E are the visibilities of the coincidence patterns.

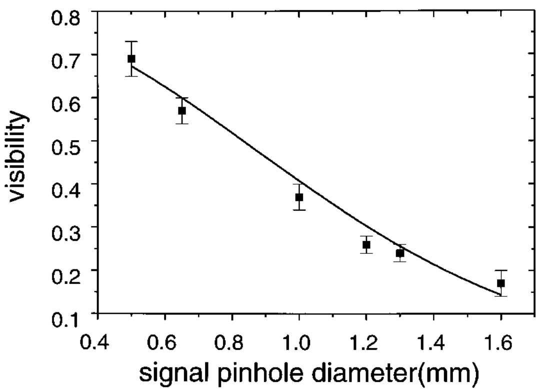

FIG. 3. Fitting of the experimental visibilities of the ghost interference patterns to a classical coherence theory.

could be described by simple classical equations. Now, an experiment is set to perform measurements of ghost interference patterns. The setup used is different from the one described in Ref. [3], essentially because type I phase-matching down-conversion is used and with a nondegenerated twin pair.

Figure 1 shows the outline of the experimental setup. The argon-ion laser pumps a $LiIO_3$ crystal with a beam of 351.1 nm wavelength. The signal beam reaching the double slit was chosen with 788.7 nm wavelength, while its conjugated twin, with 632.8 nm wavelength, propagates freely to the idler detector. The beams are detected with single photon counting modules with detector sizes of ~ 200 μm. In the idler beam, a cylindrical lens ($f = 10$ cm) was used to focus the beam only parallel to the plane of the pump, signal, and idler beams. The idler detector is 10 cm from the lens. Normal to this plane, no focalization occurs. The fringes are scanned along this normal.

In the signal beam, light passing through the double slits is collected by a detection system consisting of a variable pinhole aperture placed near (2 cm) to a spherical lens and a 200 μm avalanche photodiode (APD) detector at the focal plane ($f = 10$ cm) of the lens. The pinhole aperture defines the detection area and simulates detectors with different areas or, in other terms, the effective ghost source areas. The slits have widths of 80 μm and $d = 90$ μm is the distance between them.

The idler detection is performed through a 10 nm bandwidth interference filter and the signal through a CS-7.69 Corning optical filter of about 40 nm bandwidth. The idler detector was placed at 50 cm from the crystal. The double slit was at 10 cm from the crystal and the pinhole at 26 cm from the slits in the signal beam. Ghost interference patterns were measured for six diameters of the signal pinhole. The goal is to vary the ghost source size and analyze the coincidence fringes visibility. If the ghost coherence area behaves as the one for real sources, we should see the decrease of the coincidence fringes visibility with the increase of the ghost source size.

Figure 2 shows the ghost interference patterns for six signal pinhole diameters. As in the case of a real light source, the visibility decreases when the signal pinhole diameter is increased, or the ghost source size is increased. These results are fit to the equation for the spatial degree of coherence of a real Gaussian source [5]

$$\mu = \exp\left(-\frac{k_s^2 d^2 a_g}{r^2} \right), \tag{4}$$

where k_s is the signal wave number, d is the separation between slits, r is the distance between the ghost source and the slits, and a_g is the ghost source width in the direction parallel to the scan. The fit shown in Fig. 3, agrees with Eq. (4) for $d = d_{eff} = 130$ μm and imposing an upper bound for the visibility $\mu_{eff} = 0.8$. Although the separation between slits is $d = 90$ μm, $d_{eff} = 130$ μm is acceptable because of their finite width (80 μm). The upper bound for the visibility can be viewed as a phenomenological compensation for experimental limitations for observing the maximum visibility. This approach was used, for example, in Ref. [6].

The experimental results and the discussion about results of Ref. [1] show that the idea of ghost sources associated to the classical theory can be useful for describing the visibilities of the fringes obtained in double-slits coincidence measurements.

The idea of ghost source was used to explain effects observed in direct interference coincidence measurements. This emphasizes that *direct* and *ghost* interference are just manifestations of the same correlation between twin photons, as a signal ''object'' and its conjugated idler ''image.'' The theoretical arguments developed by Ref. [3] were applied to the nondegenerated down-conversion. The effect of ghost interference was observed using type I phase-matching down-conversion and a nondegenerated twin pair.

It was shown that if one of the detectors can be viewed as a ghost source in one double-slit coincidence experiment, classical first-order coherence functions can be used to predict the visibilities of the coincidence patterns. This approach works for direct and for ghost interference. This idea succeeds in explaining the results of Ref. [1], where fringes disappear when the idler detector pinhole diameter is increased. It is also quantitatively reasonable if an upper bound for the visibilities is assumed due to experimental difficulties.

For the ghost interference, these results show experimentally that the visibility depends on the ghost source size in the same way as real light sources. Despite this relative success of the idea of the ghost sources and images, we believe that a complete theory must be developed.

As stressed in Ref. [1], the fourth-order correlation function for the electric field of the down-converted light, should be written with a multimode theory [7], to reveal the entanglement between coherence areas of the signal and idler light. This function should show explicitly all transverse spatial correlation within the down-converted light. Consequently, it could generate any conjugated ''image'' produced by a given ''object,'' as the direct or ghost patterns, without relying on the idea of using detectors as fictitious sources. This would be a very basic *quantum-image* theory [8] for *free* down-converted light.

This work was supported by the Brazilian research funding agencies CNPq, FINEP, and FAPEMIG.

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