Transmission of Quantum Images Through Long Distances

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We report on an experiment demonstrating the principle for transmitting quantum images through long distances. Signal and idler beams carrying correlated images have natural divergences that can be compensated by the use of collimating lenses and at the same time preserving the information contained in their correlated angular spectra.

42.50.Ar, 42.25.Kb

I. INTRODUCTION

The use of the quantum entanglement for practical applications consists in a formidable challenge. The twin photons produced in the parametric down-conversion, can be prepared in entangled states that can be used for instance, in quantum communication [1]. Most of the projects related to the use of entangled photons for quantum communication, rely on the manipulation of the photon polarization as the entangled degree of freedom [2]. In particular, the capability of reliably transmitting an entangled photon pair through a long distance have been pursued, with [3] and without [4] the use of optical fibers. Optical fibers are a very convenient and robust medium for transmitting optical signals. However, sometimes it is not possible to use it. One nice example is the project for transmitting entangled photon pairs via satellite [5]. As a first approach, it has been demonstrated that it is possible to share an entangled photon pair through about 600m of free air [6]. In all the cases mentioned, the entangled degree of freedom was the polarization. In this paper, we are going to show that it is also possible to share entangled photon pairs through long distances, manipulating other degree of freedom: the transverse momentum of the photon. Twin photons entangled in the transverse momentum give rise to the so called Quantum Images. The term quantum image has been used for the correlated images in optical fields [7]. A discussion on the issue of the quantum character of these correlated images is actually in progress [8]. In this work, we are going to deal with correlated images transferred from the pump to the correlated angular spectrum [9]. In this case, it is possible to show that some correlated images, have transverse correlations that violate a classical inequality, leading to spatial photon anti-bunching [10,11]. The present work is based in this kind of correlated images and we going to call them quantum images, even though there may have place for further discussion on the issue. We are going to demonstrate that it is possible to transmit a quantum image through the free air for long distances. The scheme consists in compensating the divergence of the signal and idler beams without losing the spatial correlations between them. First, we show how the use of collimating lenses increase the coincidence counting rate spatial density and second we demonstrate the transmission of a correlated image through about 3m.

II. THEORETICAL BACKGROUND

![Experimental setup used to produce quantum images.](image)

FIG. 1. Experimental setup used to produce quantum images that are prepared by manipulating the pump beam before the nonlinear crystal. The lens L is used to project the image of the mask M1 onto the detection plane.

We are going to deal with quantum images that are prepared by manipulating the pump beam before the nonlinear crystal. In general, some transverse pattern can be measured by displacing signal and/or idler beam detector while performing coincidence detection. See Fig. 1. Signal and idler beams freely propagate from the crystal to the detection planes and the coincidence counting rate is given by [9]

\[ C(\rho_s, \rho_i) \propto |W[(\rho_s + \rho_i), Z_{AD}]|^2, \]  

(1)

where \(\rho_s, \rho_i\) are the transverse coordinates of the signal and idler detectors respectively, \(W\) is the pump field amplitude distribution in a plane at the same distance from the crystal as the detectors (we have considered the same distance for both D1 and D2), \(Z_{AD}\) is the distance between crystal and detectors and the down-conversion was assumed to be degenerated. If one wants to send the information contained in the correlated image through long distances, there is a drawback in using this kind of system [12], because signal and idler beams are naturally diverging beams as they are generated by a cavity free finite source. The coincidence counting rate through fixed detection surfaces is reduced, depending on the pump laser spot size inside the crystal and on the crystal length. In some cases, even though the information in the correlated image is still preserved, the time for performing the measurement increases as the coincidence counting rate decreases. Finally, a limit is reached where the signal to noise ratio is too low and the information is lost. We
have calculated the coincidence counting rate, analogous to Eq. 1, taking into account the divergence of the signal and the idler beams:

\[
C (\rho_s, \rho_i) \propto \left( \frac{k_p}{Z_{AD}} \right)^2 W \left[ (\rho_i + \rho_s), Z_{AD} \right]^2 , \tag{2}
\]

where, \(k_p\) is the wavenumber of the pump beam. As expected, the image is still transmitted, but now there is a factor depending on the inverse of the distance from the crystal to the detection plane \(Z_{AD}\) multiplying the coincidence counting rate. This factor is usually ignored, because in general we are more interested in the spatial modulations of the coincidence profile than the absolute number of coincident pairs. The expression above is still defined unless a multiplicative factor, the difference from Eq. 1 is that now the dependence on the distance \(Z_{AD}\) appears explicitly, showing the reduction of the number of coincident photons per unit area. In order to circumvent this problem, it is necessary to use collimating lenses for signal and idler beams, but without disturbing the image entanglement. The combination of actions on the pump beam and on the signal and idler beams for obtaining correlated images has been demonstrated in Ref. [13]. It has been shown that a diffracting mask can be placed in the pump beam before the crystal, while one imaging lens is placed in the path of collinear twin beams for obtaining the correlated image. This means that the propagation of the correlated image was changed by the imaging lens in the signal and idler beams. The effect of this lens in the correlated image is the same effect of a lens placed in the pump beam, for its intensity image.

The coincidence counting rate in this case is given by [13]

\[
C (\rho_s, \rho_i) \propto W \left[ \frac{O}{I} (\rho_i + \rho_s) \right]^2 , \tag{3}
\]

where \(O\) is the distance between the diffracting mask and the lens (even if part of the path is in the pump and part in the signal-idler) and \(I\) is the distance between lens and image plane (detection plane).

Eq. 3 was obtained for the collinear and degenerate case. However, for technical reasons, we have used non-collinear and non-degenerate twin pairs. In Fig. 2a it is shown a typical experimental set-up, where a diffracting mask is placed in the pump beam, before the crystal and similar lenses are placed in the signal and idler beams. As the experimental results are going to demonstrate, Eq. 3 is still valid for our set-up, because the non-degeneracy is small. The ratio between \(k_s\), \(k_i\) and \(k_p/2\) (the degenerate wavenumber) are respectively 0.95 and 1.05 and therefore the difference is not significant. The fact that they are non-collinear is not a problem neither, because even for the collinear case, signal and idler are already independent modes.

The relation between variables \(I(\text{image})\) and \(O(\text{object})\) in Eq. 3 and the set-up in Fig. 2a is given by \(O = Z_{m1} + Z_L\) and \(I = Z_D\) (The distance between lens L2 and detector D2 in the idler beam is also \(Z_D\)). \(W\) is the pump field amplitude distribution at the mask position, \(Z = 0\). Eq. 3 shows that the information about the angular spectrum of the pump beam scattered through mask M1 is preserved in the correlation between signal and idler photons, after propagation through lenses L1 and L2.

\[\text{III. EXPERIMENT AND RESULTS}\]

First, we demonstrate the effect of the divergence of the signal and idler beams in the coincidence counting rate, for a correlated image prepared in the pump beam.
The experimental scheme is sketched in Fig.1. We use a femtosecond modelocked Ti-Safire laser, for obtaining pulses with the central wavelength around 850nm. Second harmonic generation is performed in a 2mm long type I BBO crystal, producing pulses with wavelength centered around 425nm.

These pulses are used to pump a 5mm long LiIO\(_3\) crystal, also type I phase matched. Non collinear and non degenerate twin beams are detected through a narrow band interference filter (\(\Delta \lambda \approx 10\,nm\)), centered around 890nm for the signal, and a wide band interference filter (\(\Delta \lambda \approx 40\,nm\)) centered around 800nm for the idler. The image to be transmitted is obtained from the diffracting mask M1. It consists in a thin wire. This is a very simple object and its image contains low frequency modulations. This is convenient, as in this case it is possible to work with relatively large apertures in the detection, in order to have considerable coincidence counting rates, and at the same time having resolution for measuring the image. If one wants to transmit images containing small details, higher pump power and/or higher down-conversion efficiency is required. M1 is imaged by lens L, with the pump beam passing through the crystal, in a plane situated about 70cm from the crystal. The image seen in the intensity distribution of the pump beam can be reconstructed in a correlated image by scanning signal detector, with the idler detector fixed (or vice-versa) [9].

This image is shown in Fig.3a. Because of the divergence of the signal and idler beams, when the distance between the crystal and the detectors increase, the coincidence counting rate decreases for fixed detectors surfaces. This divergence can be compensated by placing collimating lenses L1 and L2 in the signal and idler beams, respectively, and withdrawing lens L in the pump beam. See Fig. 2a. These lenses image the quantum image in the detection plane, and at the same time they collimate signal and idler beams. The correlated image is measured exactly in the same way as before and the result is shown in Fig.3b. Note that the coincidence counting rate in each point is increased by a factor of about 10.

Second, we use the principle demonstrated above for detecting a correlated image in a plane situated about 3m from the crystal. In this case, it is difficult to obtain the correlated image without the use of lenses in the down-converted beams. One imaging lens placed in the pump beam, should have a focal length of the order of meters for giving rise to an image with the same size as the object. Therefore it should be placed far from the object and the diffraction would be a problem for lenses with the typical diameters of about 25mm. On the other hand, using collimating lenses in the signal and idler beams, the quantum image was transferred with a good coincidence counting rate, comparable to the previous measurements in Fig.3b. Besides the lenses L1 and L2, it was necessary to use other lenses, L3 and L4. See Fig.2b. They are necessary, in order to form a telescope with lenses L1 and L2 and to keep the image with its original size. The resulting coincidence transverse distribution is displayed in Fig.4.

**FIG. 3.** (a) Image of the mask M1 without use of lenses in the signal and idler beams. (b) Image of the mask M1 with use of lenses in the signal and idler beams. Lines are only a guide to the eye.

**FIG. 4.** Image of the mask M1 detected at 3m from the crystal, with use of additional lenses L3 and L4. Lines are only a guide to the eye.
IV. CONCLUSION

In conclusion, we have demonstrated how the natural divergence of the signal and idler beams produced in the spontaneous parametric down-conversion can be compensated with collimating lenses, without loosing the quantum correlation between their angular spectra. It is proposed that this scheme can be used for sending quantum images through long distances. The idea of using correlated images in cryptographic protocols have been raised in Ref. [14] and that could be associated to this long distance transmission scheme.

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