# Generation of spatial antibunching with free-propagating twin beams

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We propose and implement a method to produce a spatial antibunched field with free-propagating twin beams from spontaneous parametric down-conversion. The method consists in changing the spatial propagation by manipulating the transverse degrees of freedom through reflections of one of the twin beams. Our method uses reflective elements, eliminating losses from absorption by the objects inserted in the beams.

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## I. INTRODUCTION

In contrast with light sources where the emitted photons tend to propagate together, special kinds of light sources can produce photons tending to propagate separately in time or space. This effect, referred to as photon antibunching, has been predicted in time [1] and spatial [2] domains and observed in resonance fluorescence by excited atomic beams [3], trapped ions [4], trapped molecules [5], and in optical parametric process [6,7]. Recently, Nogueira, Walborn, Pádua, and Monken [7] have proposed and implemented a spatial version of the photon antibunching where photons tend to propagate separately with respect to the transverse propagation plane. They have used twin photons from the parametric down-conversion and in their experiment, the final state is prepared by propagation through special double slits, leading to a light beam in which photons seem to repel each other in space.

In this work, we propose and implement an experimental scheme for obtaining spatial antibunching with free-propagating beams. It is based on the transfer of the angular spectrum from the pump to the twin beams of the down-conversion [8] and the manipulation of the transverse spatial coordinate of one of the beams. We obtain a high quality antibunched beam. The preparation of the state is very efficient with respect to the incoming signal and idler beams.

## II. STATE PREPARATION

In order to produce spatial antibunching, one light beam must be able to violate a classical inequality for its fourth-order correlation function in the spatial variables (see Eq. (11) of Ref. [7]):

$$\Gamma^{(2,2)}(\boldsymbol{\delta}) \leqslant \Gamma^{(2,2)}(0), \tag{1}$$

where

$$\Gamma^{(2,2)}(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2, \tau) = \langle \boldsymbol{I}(\boldsymbol{\rho}_1, \tau) \boldsymbol{I}(\boldsymbol{\rho}_2, t+\tau) \rangle, \tag{2}$$

$\boldsymbol{\delta} = \boldsymbol{\rho}_1 - \boldsymbol{\rho}_2$ is the distance between the two points where the correlation function is evaluated and $\tau = 0$.

This kind of correlation function is usually measured with coincidence photon detection schemes, as described in Fig. 1, for example. The light beam is sent through a 50/50 beam splitter and coincidence measurements are performed between detections at detectors D1 and D2 for different positions of these detectors in the transverse plane. Therefore, the inequality in Eq. (1) would be violated whenever the coincidence-counting rate for displaced (in the transverse detection plane) detectors is bigger than that for aligned ones.

According to previous works [8], it is possible to manipulate the transverse profile of the coincidence-counting rate between signal and idler photons from the parametric down-conversion by manipulating the pump beam profile. Therefore, we would be able to prepare collinear twin beams that would give rise to a transverse coincidence distribution which would violate the inequality in Eq. (1). This requirement is easily fulfilled preparing the pump beam with zero intensity in its center. As this intensity distribution is transferred to the coincidence distribution, we would have zero coincidences for aligned detectors and some higher coincidence-counting rates for displaced detectors.

There is, however, one problem. The violation of the inequality only results in the spatial photon antibunching if the light beam is homogeneous. This means that the intensity (second-order correlation function) should be constant along the detection region and the coincidence-counting rate (fourth-order correlation function) must depend only on $\delta$, the relative displacement between detectors D1 and D2. This last requirement is not fulfilled by the state preparation by manipulation of the pump beam. The coincidence-counting rate depends on the pump beam profile in the sum of the spatial variables [8]:

$$C(\rho_i, \rho_s) \propto \left| \mathcal{W}\left( \frac{\rho_s}{\mu_s} + \frac{\rho_i}{\mu_i} \right) \right|^2, \tag{3}$$

where $\mathcal{W}$ is the field transverse distribution of the pump, $\rho_i$ and $\rho_s$ are the transverse coordinates at the detection plane,

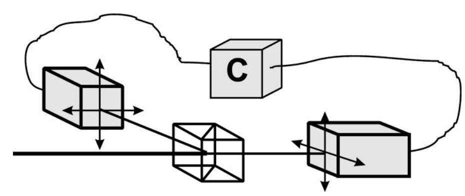


FIG. 1. Scheme to measure the second-order correlation function.

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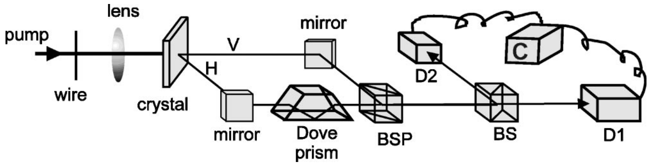


FIG. 2. Experimental setup.

and $\mu_i$ and $\mu_s$ are coefficients depending on the distances between signal and idler detection planes to the crystal.

The dependence of the coincidence-counting rate on the sum of the position variables above characterizes the nonhomogeneity of this field. Therefore, the violation of the inequality in Eq. (1), does not imply spatial antibunching. In the following, we propose and implement a simple method for obtaining homogeneity, and as a result, the antibunching.

The experimental setup is shown in Fig. 2. Before the pump laser reaches the nonlinear crystal, it is passed through a thin wire and through an imaging lens, so that after pumping the crystal, the image of the wire is formed in a plane situated at a certain distance from it. This distance is the same as the distance between crystal and detectors. It has been demonstrated that the coincidence-counting rate between signal and idler photons has a transverse distribution that mimics the pumping beam intensity distribution [8]. This will lead to a coincidence-counting rate which is zero when the detectors are aligned and increases when they are displaced. As stated above, this field is nonhomogeneous.

In order to overcome this difficulty, we have utilized the scheme displayed in Fig. 2. Signal and idler beams from type-II phase-matching down-conversion are produced in a noncollinear configuration. The signal beam is passed though a Dove prism, so that its spatial coordinate $y$ is changed into $-y$. As signal and idler have orthogonal polarizations, signal and idler beams can be fully recombined in a polarizing beam splitter. The recombined beam is split in a nonpolarizing beam splitter and the two output beams are sent to detectors. Now, the coincidence-counting rate for scans in the $y$ direction is given by

$$C(\rho_i,\rho_s)\propto\left|\mathcal{W}\left(\frac{\rho_s}{\mu_s}-\frac{\rho_i}{\mu_i}\right)\right|^2. \qquad (4)$$

This characterizes a homogeneous field and, as it still keeps the pump image information, it will give rise to spatially antibunched photons. The experimental demonstration is easier in one dimension, but the result can be easily extended for the two-dimensional case by insertion of a second Dove prism rotated by 90° with respect to the propagation axis in any one of the beams.

There are two important differences between this scheme and the one implemented in Ref. [7]. There, the modulation in the coincidence distribution comes from the interference due to the propagation through a double slit. Here, it comes from the state preparation through the pump beam angular spectrum. Another difference is that in Ref. [7] a quarter-wave plate is placed in front of each slit with orthogonal fast axis to introduce a phase shift in the coincidence interference fringe. Here, a Dove prism is used for inverting the transverse coordinate of the wave front of one of the twin beams.

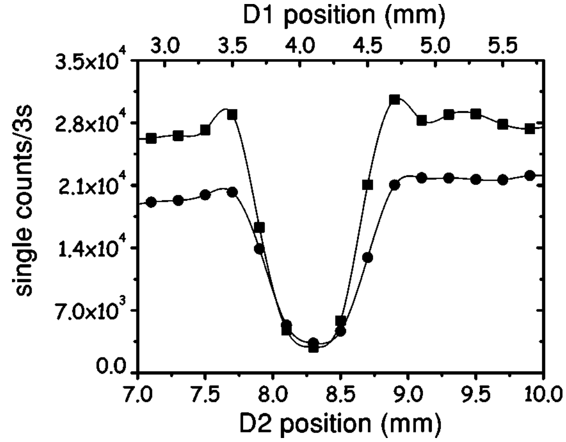


FIG. 3. Intensity profile scanning D1 (squares) and D2 (circles).

Because our method acts in the state preparation, and the propagation through the Dove prism is almost lossless, the amount of the spatially antibunched photons is larger than in Ref. [7].

## III. EXPERIMENT

The experiment has been performed with a cw horizontally polarized HeCd laser operating at 442 nm pumping a 1-cm-long BBO crystal cut for type-II phase matching, as shown in Fig. 2. The down-converted signal and idler beams, at 884 nm, emerge from the crystal at an angle of 11° with respect to the laser beam. Two mirrors and a polarizing beam splitter recombine the twin beams. In the signal path a Dove prism is inserted to produce the homogenous field distribution in the second order. The combined beam propagates to a nonpolarizing beam splitter and are sent to detectors D1 and D2 placed about 75 cm from the crystal. Each detector assembly includes a slit of about 0.3 mm width, an interference filter centered in 884 nm with 10 nm bandwidth, a 12.5-mm focal-length lens, and a single-photon counting module. The detectors are mounted on translation stages. Single and coincidence counts are recorded scanning the detector in $y$ direction.

## IV. RESULTS AND DISCUSSION

We begin by calibrating the position where detectors receive light from the same point of the nonpolarizing beam splitter (BS). This is achieved by inserting a thin (500 $\mu$m diameter) wire in the beam, before the beam splitter, scanning both detectors, and measuring the single-photon counting rates. Figure 3 shows the single counts as a function of D1 and D2 positions. In the position where each intensity is a minimum, detectors D1 and D2 will be looking at the same point in the beam splitter, just like a two-photon detector. Now, we remove the wire before the BS and place a 250-$\mu$m diameter wire and a 25-cm-focal-length lens in the path of the laser beam before the crystal, such that after the crystal,

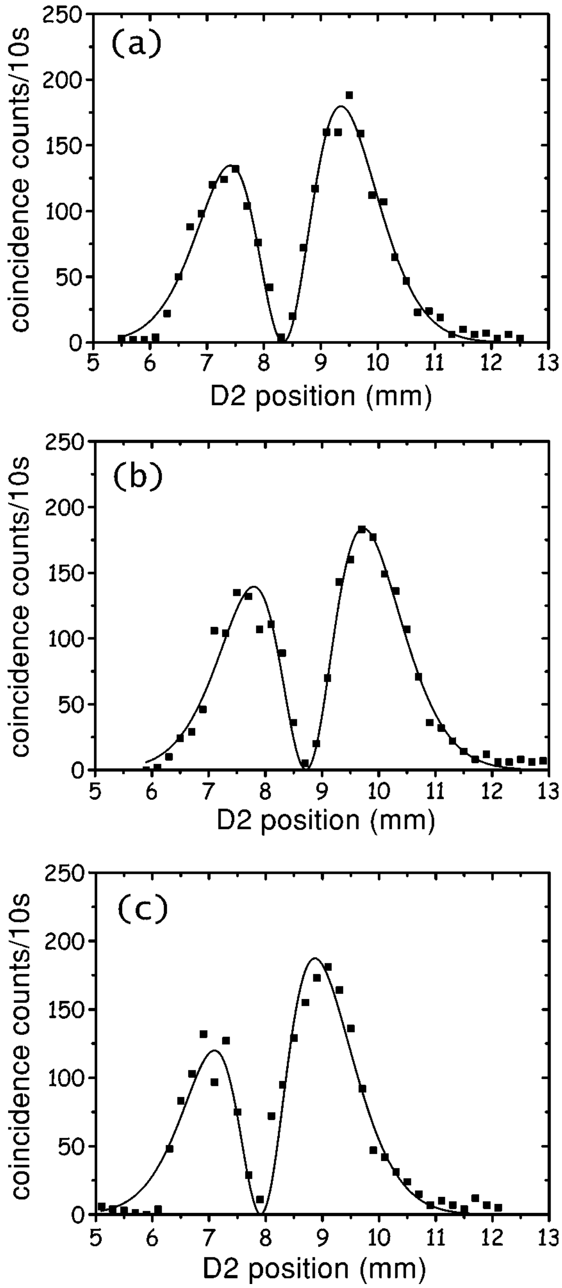


FIG. 4. Coincidence profile scanning D2 with D1 fixed. (a) D1 at the minimum of the profile in Fig. 3; (b) D1 displaced by +0.4 mm; and (c) D1 displaced −0.4 mm.

the image of the wire is formed in a plane situated at the same distance from the crystal to the detectors. In Fig. 4(a) the coincidence profile scanning D2 and keeping D1 at the calibration point (minimum in Fig. 3) is shown. As we can see, the image of the wire in the laser beam is transferred to the coincidence-counting rate according to the transfer of the angular spectrum [8]. We repeat this measurement with D1 displaced by +0.4 mm and −0.4 mm from its previous position, and the results are shown in Figs. 4(b) and 4(c), respectively. The effect of displacing D1 is the shifting of the coincidence image by the same quantity, showing conditional behavior. Scanning D1 and D2 simultaneously in the same sense, the coincidence counting rate is constant and equal to the minimum of the profile in Fig. 4(a), while scanning simultaneously and in the opposite sense, the coincidence-counting rate depends on the sum of the transverse coordinates of the signal and idler detectors. The coincidence profiles for these two situations are shown in Fig. 5. In Fig. 5(a) we can see a background at the level of the minimum in Fig. 4(a), illustrating the homogeneous (dependence only on the difference of the spatial coordinates) character of the field to the fourth order, while in Fig. 5(b) the image in coincidence appears about two times smaller than that of Fig. 4(a).

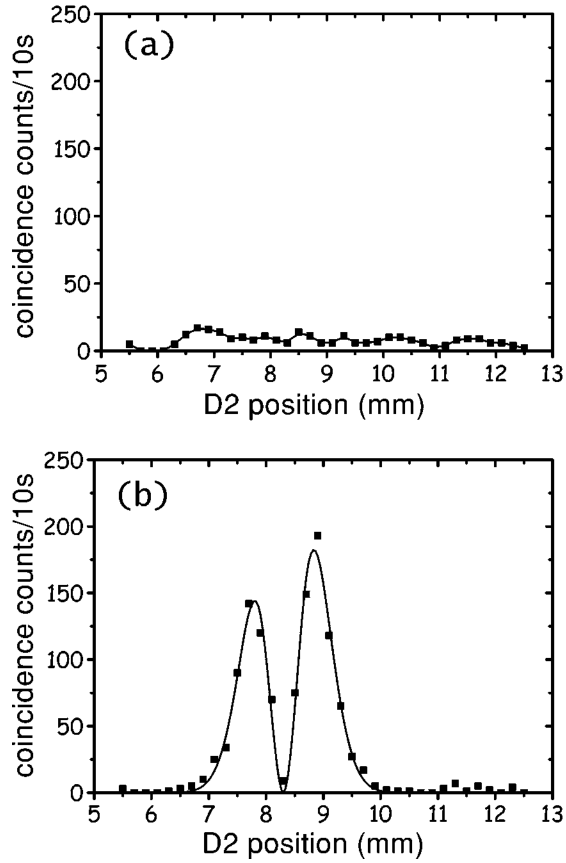


FIG. 5. Coincidence profile scanning D2 and D1 simultaneously plotted as a function of D2 position. (a) Same sense and (b) opposite sense.

We have also performed the same kind of measurement as before, without the Dove prism. The transferred image to the coincidence-counting rate is shown in Fig. 6(a), while the effect of the displacement of D1 +0.4 mm and −0.4 mm, from its central position is shown in Figs. 6(b) and 6(c), respectively. In contrast with the situation described above, the image in coincidence is shifted in the opposite sense with respect to the displacement of D1. Scanning D1 and D2 simultaneously, in the same sense, the coincidence-counting rate is not anymore constant, while scanning in the opposite sense it is constant and equal to the minimum of the profile in Fig. 6(a). These results are shown in Fig. 7. Here, the coincidence-counting rate depends on the sum of the transverse coordinates of the signal and idler beams, so that the field is no longer homogeneous to the fourth order; see Fig.

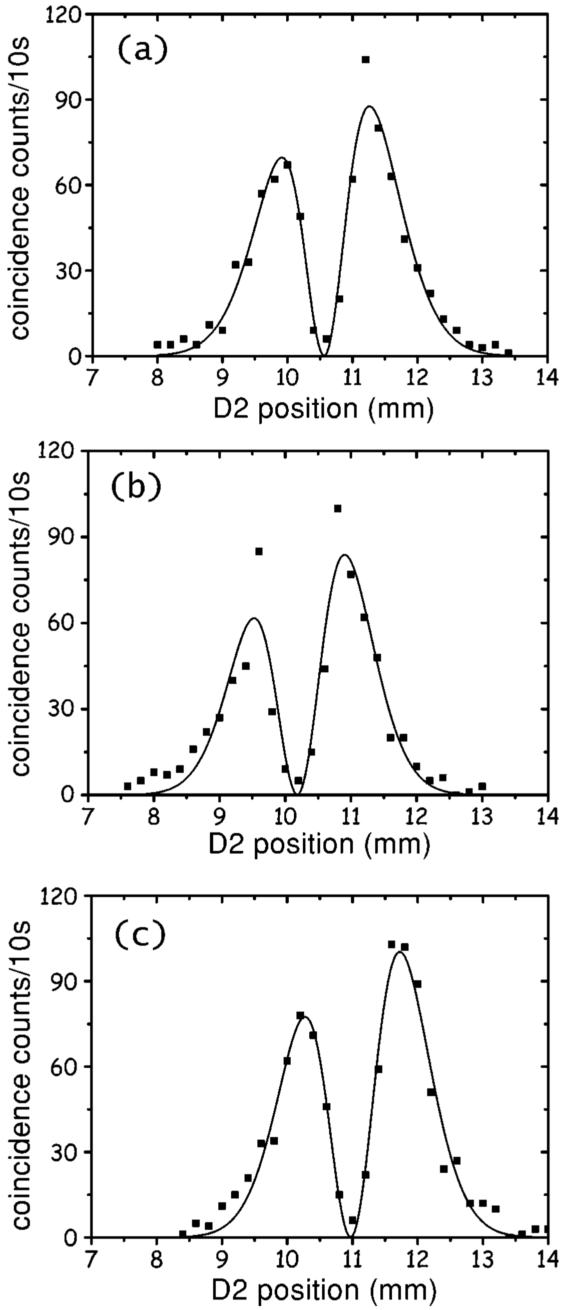


FIG. 6. Coincidence profile scanning D2 with D1 fixed. (a) D1 at the minimum of the profile in Fig. 3; (b) D1 displaced by +0.4 mm; and (c) D1 displaced by −0.4 mm.

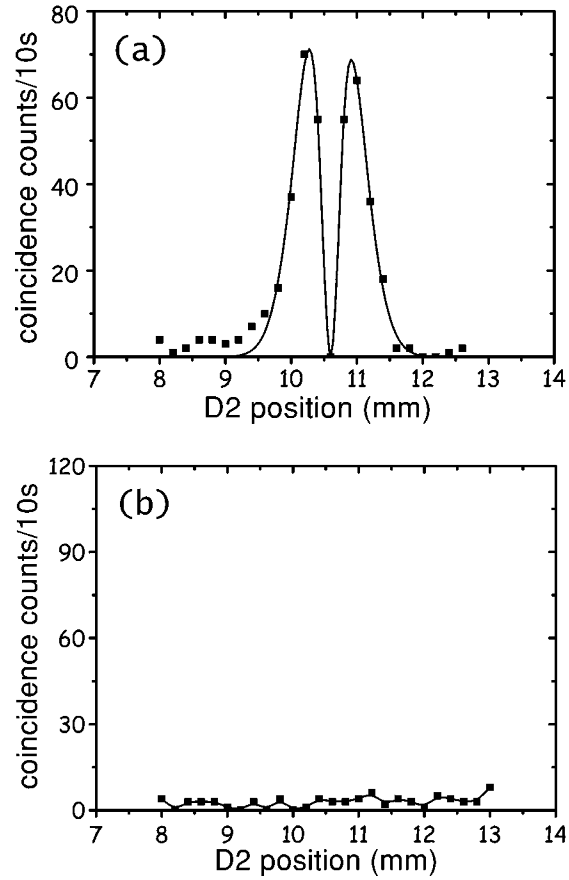


FIG. 7. Coincidence profile scanning D2 and D1 simultaneously plotted as a function of D2 position. (a) Same sense and (b) opposite sense.

7(a). In this case the results cannot be interpreted as spatial antibunching.

One important issue is the fact that no losses are imposed on signal and idler modes during the preparation process. This improvement might be useful for applications of this kind of nonclassical light, because the coincidence-counting rates can be higher than those of Ref. [7]. Possible applications might be related to efficient and precise weak light imaging and also measurement of small displacements with weak light, in a similar way as is done in Ref. [9]. Anyway, to the best of our knowledge, these are only possibilities that have not yet been developed.

Another issue is the quality of the state prepared. One way of evaluating this quality is through the normalized fourth-order correlation function defined by

$$g^{(2,2)}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)=\frac{\langle \boldsymbol{I}(\boldsymbol{\rho}_1)\boldsymbol{I}(\boldsymbol{\rho}_2)\rangle}{\langle \boldsymbol{I}(\boldsymbol{\rho}_1)\rangle\langle \boldsymbol{I}(\boldsymbol{\rho}_2)\rangle}, \tag{5}$$

where $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$ are the transverse positions of the detectors D1 and D2, respectively. A parameter to quantify the quality of the antibunching produced can be defined as the ratio between the maximum value of $g^{(2,2)}(\boldsymbol{\rho}_1 \neq \boldsymbol{\rho}_2)$ and the value of $g^{(2,2)}(\boldsymbol{\rho}_1=\boldsymbol{\rho}_2)$. For the result shown in Fig. 4(a) this ratio is about 47. Therefore, comparing with the results of Ref. [7], where this ratio was about 9, we have produced a higher quality, spatially antibunched beam.

## V. CONCLUSION

We have proposed and implemented a scheme for obtaining spatial antibunching from free-propagating signal and idler beams from the down-conversion. The scheme consists in inverting the transverse spatial coordinate of one of the twin beams. In addition to the preparation of the fourth-order correlation between signal and idler by manipulation of the pump beam, we have succeeded in obtaining a homogeneous beam that violates a classical inequality and therefore presents spatial antibunching. This method is very efficient with respect to the initial (just after emission) signal and idler beams and presents high quality antibunching.

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