Biphoton interference with a multimode pump

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We study the interference of biphotons generated via spontaneous parametric down-conversion from a pump with several longitudinal modes. It is shown that biphotons can interfere if the time difference between their birth moments is a multiple, to an accuracy of the pump coherence time, of $T\equiv 2L/c$, where L is the pump cavity length. This effect, although observed with a cw pump, is similar to a recently reported interference of biphotons generated from time-separated pump pulses.

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The effect of two-photon interference plays an important role in quantum optics. This nonclassical effect can be observed for biphoton fields generated, for instance, via spontaneous parametric down-conversion (SPDC) [1]. A biphoton is a pair of photons (called signal and idler photons) correlated in time, frequency, wave vector, and polarization. The simplest way to discover this correlation is to observe coincidences between the counts of two detectors registering signal and idler radiation, respectively. The coincidence counting rate is many orders higher than one could expect if the detectors were illuminated by independent radiation sources. There are two basic ways to observe two-photon interference.

(1) In some experiments, biphoton fields are generated in different spatially separated domains [2] or from temporally separated pump pulses [3]. In this case, interference reveals itself in the dependence of the coincidence counting rate on the phase shift introduced between the biphotons emitted by different space or time domains where SPDC takes place. This can be a shift of one crystal with respect to another, or a delay introduced between two pump pulses. It is important that, in this case, the interference pattern observed in coincidences has 100% visibility.

(2) In other works, biphoton radiation is fed into some linear interferometer [4–6]. In this case, interference is observed as the dependence of coincidences at the output of the interferometer on the phase shift introduced between the arms of the interferometer. In some cases, only 50% visibility is achieved in experimental schemes of this kind [4,7]: a photon pair can be split at the input port of the interferometer, and if the coincidence circuit time resolution is larger than the delay introduced between the arms of the interferometer, such events cannot be discarded and ''spoil'' the visibility.

One of the most remarkable features of two-photon interference is that although both idler and signal photons have very small coherence length (tens of microns), the spatial separation of the sources of SPDC radiation (in the first scheme) or the path-length difference between the interferometer arms (in the second scheme) can be much higher. In fact, the only constraint on this parameter is that it should not exceed the pump coherence length. One can show that the interference visibility depends on the path length difference ΔL as $V=|g^{(1)}(\Delta L)|$, where $g^{(1)}(z)$ is the first-order spatial correlation function of the pump. In this work, we demonstrate this dependence experimentally for the case where the pump is a cw laser with multiple nonsynchronized longitudinal modes. For this pump, $g^{(1)}(z)$ has multiple peaks separated by the distance $2L$, where L is the laser cavity length. The width of each peak is determined by the inverse width of the total contour of generation [8]. Such a laser was used as a pump in Ref. [5], where fourth-order interference was observed by directing both signal and idler photons into Michelson interferometers. The observed interference pattern had only 18% visibility, which was explained by the fact that the path-length difference exceeded the pump coherence length. In a similar experiment [6], the path-length difference was small compared to the pump coherence length, and the only factor bounding the visibility was splitting of photon pairs at the input port of the interferometer. In accordance with this, 50% visibility was observed. It should be mentioned that, in both experiments, the visibility could be increased up to 100% if the path-length difference were made larger than the coincidence resolution time. Even with a multimode pump, this was possible if the authors used not the central peak of the pump correlation function but one of its side peaks.

In this work, the main idea is to observe the interference of biphotons generated from a multimode pump with a time separation equal to $2L/c$, which corresponds to the first side peak of the pump correlation function. There is a clear analogy with experiments where interfering biphotons are generated from two coherent pump pulses [3]. A necessary condition for such interference is that the delay between the biphotons should be equal to the time interval T_p between the pulses. This condition gives an additional parameter for interference, which can be used in cryptography. However, one will see from this paper that the same parameter $T_p=2L/c$ appears if a pulse pump is replaced by a multimode cw pump, which is much easier to handle.

In our experiment, the pump is a multimode cw He-Cd laser operating at a wavelength 325 nm. The laser cavity length is 99 cm. In accordance to this, its first-order correlation function $g^{(1)}(z)$ contains multiple peaks separated by 198 cm, the full width at half maximum of each peak being 26 cm [9].

The relation between the interference visibility and the optical path length difference can be easily obtained using the same approach as in Ref. [10]. For collinear frequency-degenerate type-I SPDC, which we use in this work, the state vector has the form

$$|\psi\rangle=|\mathrm{vac}\rangle+C\int\int d\Omega d\Omega' F(\Omega,\Omega')\times a^{+}\left(\frac{\omega_0}{2}+\Omega\right)a^{+}\left(\frac{\omega_0}{2}-\Omega'\right)|\mathrm{vac}\rangle, \qquad (1)$$

where $|\mathrm{vac}\rangle$ is the vacuum state, ω_0 is the pump frequency, the signal and idler frequencies are denoted by $(\omega_0/2)+\Omega$ and $(\omega_0/2)-\Omega'$, C is a constant $(|C|\ll 1)$, and the biphoton amplitude

$$F(\Omega,\Omega')=E(\Omega-\Omega')\mathrm{sinc}\frac{l}{2}\left\{D(\Omega'-\Omega)-\frac{1}{2s}(\Omega^2+\Omega'^2)\right\}. \qquad (2)$$

In this expression, $E(\Omega)$ is the Fourier transform of the pump amplitude time dependence, l is the crystal length, and $D=u^{-1}-u_0^{-1}$ is the difference of inverse group velocities for the down-converted radiation at frequency $\omega_0/2$ and the pump, respectively. The parameter s is determined by the second derivative of the crystal dispersion dependence $k(\omega)$, $s\equiv(d^2k/d\omega^2)^{-1}$.

Now suppose that the biphoton field is fed into an interferometer with the delay Δt introduced between the arms, and, at the output, coincidences between the two detectors are registered in the Brown-Twiss scheme as a function of Δt. The coincidence counting rate is determined by the second-order correlation function

$$G^{(2)}(t,\tau)\equiv\langle\psi|E_1^{(-)}(t)E_2^{(-)}(t+\tau)E_1^{(+)}(t)E_2^{(+)}(t+\tau)|\psi\rangle, \qquad (3)$$

where $E_{1,2}^{(\pm)}$ are positive- and negative-frequency field operators at the detectors 1 and 2 and ψ is the state vector [Eq. (1)]. After writing the usual plane-wave expansion of the fields $E_{1,2}^{(\pm)}$, taking into account linear transformations of the operators in the interferometer, and doing rather simple algebra, for the correlation function [Eq. (3)] we obtain

$$G^{(2)}(\tau)\sim 4I|C|^2\{2|\mathcal{F}(\tau)|^2+|\mathcal{F}(\tau+\Delta t)|^2+|\mathcal{F}(\tau-\Delta t)|^2+[|g^{(1)}(\Delta t)||\mathcal{F}(\tau)|^2e^{-i\omega_0\Delta t}+\mathrm{c.c.}]\}. \qquad (4)$$

The correlation function does not depend on the time t due to the stationarity of the problem. The function $\mathcal{F}(\tau)$ is the Fourier transform of the function $F(\Omega)=\mathrm{sinc}(l\Omega^2/2s)$, the square of which gives the SPDC spectrum in the collinear frequency-degenerate case. The function $g^{(1)}(t)=g^{(1)}(z/c)$ is the normalized first-order time correlation function of the pump, and I is the pump intensity. In Eq. (4), we omitted the terms corresponding to second-order (with respect to the field) interference effects, which are essential for $\Delta t<\tau_{coh}$, where τ_{coh} is the width of $|\mathcal{F}(\tau)|^2$. This kind of interference was observed in Ref. [7]. The width of the correlation function $\mathcal{F}(\tau)$ is of order of tens of femtoseconds; therefore, for much larger interferometer delays Δt, second-order interference effects are not important.

In order to take into account the finite time resolution T of the coincidence scheme, Eq. (4) should be integrated over τ from $-T$ to T. As a result, the coincidence counting rate depends on the spatial delay in the interferometer, $\Delta L=c\Delta t$, as

$$R_c\sim 1+\frac{1}{2}|g^{(1)}(\Delta L)|\cos(\omega_0\Delta L/c), \quad \Delta L\leqslant cT,$$
$$\sim 1+|g^{(1)}(\Delta L)|\cos(\omega_0\Delta L/c), \quad \Delta L>cT. \qquad (5)$$

According to Eq. (5), the coincidences manifest an interference behavior if the delay in the interferometer, ΔL, is varied. The oscillation period is given by the pump wavelength λ_0. The interference visibility coincides with the modulo of the pump correlation function, and at spatial delays smaller than cT this factor should be also multiplied by 1/2. This multiplier results from the second and third terms in Eq. (4). It has a simple interpretation: in 50% of cases, biphotons are ''split'' at the input of the interferometer, so that the signal photon travels through the long path and the idler photon travels through the short path, or vice versa. For $\Delta L\leqslant cT$, such pairs cause coincidences; at the same time, they do not make a contribution to interference since such events are distinguishable; see Refs. [4,7]. Thus, for the multimode pump used in our experiment, the visibility measured as a function of ΔL should have multiple peaks separated by the double cavity length L.

The experimental setup is shown in Fig. 1. A 5-mW cw multimode pump with the wavelength 325 nm enters a 15-mm-long $LiIO_3$ crystal cut for type-I degenerate collinear spontaneous parametric down-conversion. Biphotons emitted from the crystal have a wavelength of around 650 nm and a horizontal polarization. They are directed into a Michelson interferometer. The pump is cut after the crystal by the filter F. The retardation plate ($\lambda/2$) rotates the biphoton polarization by 45°, so the biphotons are 50% split by the polarizing beamsplitter (PBS1). Retardation plates ($\lambda/4$) in each arm of the interferometer rotate the polarization by 90° as the radiation travels from and to the splitter. Thus the SPDC beams from both arms of the interferometer, having horizontal and vertical polarization, respectively, leave the interferometer through the same output port. A half-wave plate at the output of the interferometer rotates polarization by 45°. Coincidences are measured in the Brown-Twiss scheme consisting of a polarizing beamsplitter (PBS2), two detectors (A and B), and a coincidence circuit (CC) with 1.9-ns-wide gating window. Each detector is an avalanche diode cooled to $-30\,°\mathrm{C}$. The spectral band (10 nm) is selected by the interference filter IF [11] and the near-collinear angular range (4×10^{-4} rad) is selected by a collecting lens L with focal length 50 cm and a pinhole P placed in its focal plane. The size of the pinhole has an essential influence on the interference visibility: for a fixed nonzero delay ΔL in the interferometer, interference leads to an angular distribution of coincidences, similar to the intensity distribution in an unbalanced Michelson interferometer. The angular size of the central zone in this distribution is $\sqrt{\lambda_0/\Delta L}$. If a larger angle is selected by the pinhole P, then the interference pat-

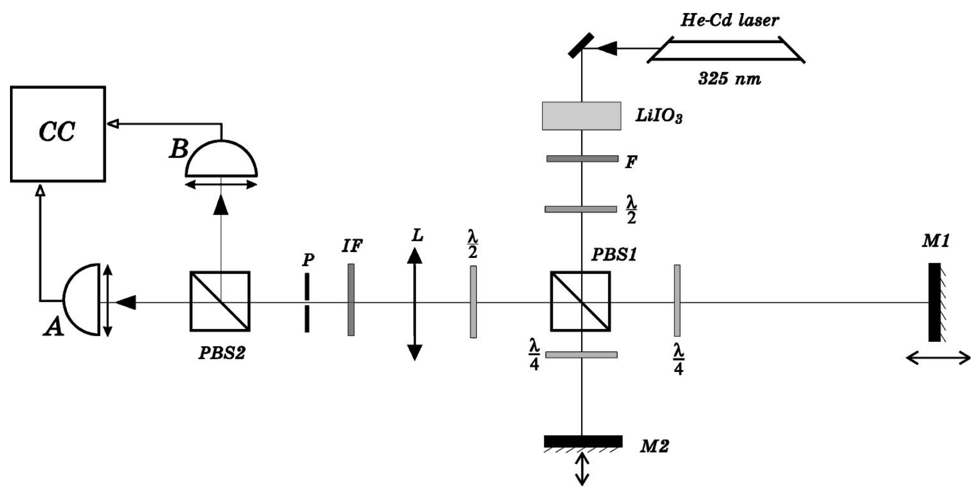

FIG. 1. Experimental setup. A frequency-degenerate collinear type-I SPDC is generated in a lithium iodate crystal from a multi-mode pump (He-Cd laser). After the crystal, the filter *F* cuts the pump radiation, and the polarization of the SPDC radiation is rotated by 45° by means of a half-wave plate. The SPDC radiation is then fed into a Michelson interferometer through a polarizing beamsplitter PBS1. Two quarter-wave plates in the arms of the interferometer rotate the polarization by 90° (as light passes them twice), and make biphotons from both arms exit from the same output port. After the interferometer, a half-wave plate rotates the polarization by 45°, so that biphotons from both arms split on the polarizing beamsplitter PBS2 and contribute to the coincidences of detectors *A* and *B*. The interference filter IF selects radiation within the band 10 nm centered at 650 nm. The pinhole *P* placed in the focal plane of the lens *L* selects near-collinear scattering.

tern is averaged, and the visibility decreases. According to this, two pinholes were used: a larger one, with a diameter 200 μm, and a smaller one, with a diameter 100 μm.

Due to the half-wave plate at the output of the interferometer, all biphotons make contributions to the coincidences. By moving mirrors $M1$ and $M2$, the path difference between the interferometer arms can be changed from 0 to 3 m for $M1$ and by fractions of the pump wavelength for $M2$, which is scanned piezoelectrically. Interference patterns are registered either by scanning mirror $M2$ (at small ΔL, for which the interferometer is stable enough) or, at large ΔL, by leaving the interferometer for a sufficiently large time and observing the distribution of coincidences.

The results of the experiment are given in Figs. 2 and 3. In order to demonstrate that there is two-photon interference for both $\Delta L \sim 0$ and for $\Delta L \sim 2L$, we measured the interference visibility as a function of ΔL using a 200-μm pinhole *P* (Fig. 2, filled circles). One can see that, indeed, in addition to the central peak, this dependence contains a peak shifted by $2L = 198$ cm. However, although the central peak has a height almost as predicted by the theory (50%, since the corresponding delays are smaller than cT, which is 57 cm in our case), the second peak is much lower than the predicted 100%. This is because the pinhole with a diameter of 200 μm does not reduce the visibility in the vicinity of the central peak, but at large ΔL it restricts the visibility. This fact is taken into account in the theoretical dependence plotted in Fig. 2 according to Eq. (5) (full line). Then, to make a precise measurement of the interference visibility in both peaks, we used a pinhole with a diameter 100 μm (Fig. 3). The visibility achieved in this case is 96%. For $\Delta L = 0$, using a 100-μm pinhole does not increase the interference visibility: it remains 50%. The results obtained for a 100-μm pinhole are shown in Fig. 2 by empty triangles. The corresponding theoretical dependence is shown by a dashed line. It should be mentioned here that the observed interference manifested itself only in coincidences; single-photon-counting rates for both detectors contained no modulation.

The results can be easily interpreted in the following way. For the pump radiation, field amplitudes separated by a length multiple to $2L$ are coherent. Thus the biphotons generated with this time separation are also coherent. To make these interfere, one should introduce a corresponding time delay between them. As we mentioned above, this experiment has a close analogy with experiments [3] where interfering biphotons were produced by time-separated pump pulses. These can be described in terms of the same ap-

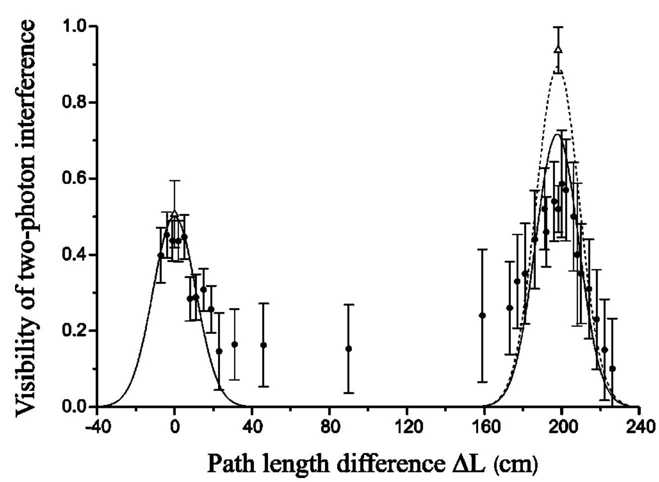

FIG. 2. Visibility of two-photon interference vs the path length difference ΔL between the arms of the interferometer. Filled circles show the data obtained using a 200-μm-diameter pinhole *P*; empty triangles show the results of measurement with a 100-μm pinhole. The full line is the theoretical dependence for a 200-μm pinhole, and the dashed line that for a 100-μm pinhole.

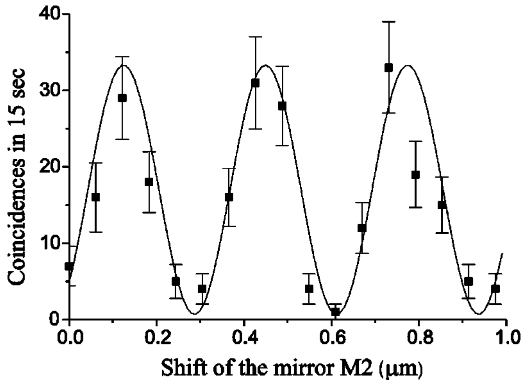

FIG. 3. Two-photon interference pattern for a path length difference $\Delta L = 198$ cm obtained with a 100-μm pinhole by scanning the mirror $M2$. A visibility of 96% is observed.

proach, based on a relation between the biphoton amplitude and the pump spectrum. Note that a pulsed pump (laser with synchronized longitudinal modes) and a multimode pump (laser with nonsynchronized longitudinal modes) have similar spectra. In contrast to pulsed SPDC where biphotons are generated only within short-time intervals, a multimode pump creates biphotons at random time moments. Nevertheless, to obtain the interference one has to make the path-length difference several times the value of the parameter $T = 2L/c$. This property could be used in quantum cryptography [12].

It should be mentioned that the same experiment could be performed with two crystals inserted into different arms of the Michelson interferometer; in this case, the visibility in the central peak would be also 100%, since there would be no biphotons with a delay introduced between the signal and idler photons.

The collinear frequency-degenerate type-I phase matching used in this experiment has a certain drawback: in half of the cases, both idler and signal photons travel to the same detector. However, this can be avoided by using a frequency-nondegenerate regime and a dichroic mirror as a beamsplitter. The rest of the experimental setup would remain the same in this case.

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[8] This is clear from the fact that the first-order correlation function is the Fourier transform of the spectrum; also see J. W. Goodman, *Statistical Optics* (Wiley, New York, 1985), p. 230.
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[11] In this experiment, the filters are used only to reduce noise. The width of the filter is not important.
[12] For instance, Alice could randomly switch between two interferometric delays, say, T and $3T/2$, and Bob could compensate for this by adding the delays 0 and $T/2$, respectively.