Quantum interference with photon pairs created in spatially separated sources

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We report on a quantum interference experiment to probe the coherence between two photons coming from non-degenerate photon pairs at telecom wavelength created in spatially separated sources. The two photons are mixed on a beam splitter and we observe a reduction of up to 84% in the net coincidence count rate when the photons are made indistinguishable. This experiment constitutes an important step towards the realization of quantum teleportation and entanglement swapping with independent sources.

I. INTRODUCTION

The principle of indistinguishability is at the heart of the quantum physical description of the world. It leads to the well-known phenomenon of interference: if two or more processes lead to indistinguishable detection events, the probability amplitude of the different processes add coherently and an interference term appears. In addition, the most well-known single photon or first order interference, interference in the coincidence detection when two or more photons can also be observed. The so-called second-order or two photon interference has been used to demonstrate non-local effects between photons forming entangled pairs. Moreover, it is as the origin of the new field of quantum information processing (for a recent overview concerning the last two points, see e.g. [4]).

Observing second-order quantum interferences with photons without common history is very important issue, since this forms the basis of entangling those photons through a so-called interferometric Bell state measurement and to demonstrate non-local effects between photons forming entangled pairs. Moreover, it is also the origin of the new field of quantum information processing (for a recent overview concerning the last two points, see e.g. [4]).

II. MANDEL DIP WITH INDEPENDENT PDC SOURCES

As shown in Fig. 1 we create pairs of non-degenerate photons in two non-linear crystals using short pump
pulses. The photons belonging to a pair are separated and two photons from different sources are superposed on a 50-50 beam splitter. We label \( a^\dagger \) and \( b^\dagger \) (\( c^\dagger \) and \( d^\dagger \)) the creation operators of the two input (output) modes respectively. Unitarity implies that the phase difference between a reflected and a transmitted photon is \( \frac{\pi}{2} \). For a 50-50 beam splitter, the evolution is thus \( a^\dagger \rightarrow \frac{1}{\sqrt{2}} (c^\dagger + id^\dagger) \) and \( b^\dagger \rightarrow \frac{1}{\sqrt{2}} (ic^\dagger + d^\dagger) \).

Suppose that we have one photon in each input mode, i.e. the following Fock state:

\[
|\psi_{in}\rangle = a^\dagger b^\dagger |0\rangle
\]  

(1)

After the beam splitter the state becomes:

\[
|\psi_{out}\rangle = \frac{1}{2} (i(c^\dagger)^2 + i(d^\dagger)^2 + c^\dagger d^\dagger - c^\dagger d^\dagger) |0\rangle
\]

\[= i \frac{1}{\sqrt{2}} |2\rangle_{c} |0\rangle_{d} + i \frac{1}{\sqrt{2}} |0\rangle_{c} |2\rangle_{d} \]

(2)

We thus find that for a 50-50 beam splitter, the two probability amplitudes corresponding to both photons transmitted and both photons reflected – i.e to both photons in different output ports – cancel out and the coincidence rate drops to zero. This description is valid of course only if the photons become completely indistinguishable after the beam splitter. If we delay the photon from one source with respect to the other one, we loose temporal indistinguishability, and the destructive interference diminishes. We define the visibility of the Mandel dip as follows:

\[
V_{\text{dip}} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}}}
\]  

(3)

In the case of two PDC sources, there are different possibilities to create 2 photon pairs at the same time: either one creates one pair in each source, or two pairs in one source and none in the other one. As already said, in order to ensure temporal indistinguishability, the coherence time of the down-converted photons must be larger than the duration of the pump pulses. This implies that the pairs created within the same laser pulse and crystal are subject to stimulated emission [16]. The output state of a non degenerate PDC follows the distribution [17] [18]:

\[
|\Psi\rangle = e^{-g} e^{\Gamma A^\dagger B^\dagger} |0\rangle = \sum_n \frac{(\tanh \zeta)^n}{\cosh \zeta} |n_A, n_B\rangle
\]  

(4)

where \( A^\dagger \) and \( B^\dagger \) are the creation operators for the PDC modes A and B, and \( |n_A, n_B\rangle \) corresponds to \( n \) photons in PDC modes A and B respectively. The parameter \( \zeta \) is proportional to the amplitude of the pump field and to the non-linear susceptibility \( \chi^{(2)} \), \( g = ln(\cosh \zeta) \) and \( \Gamma = \tanh \zeta \). In the limit of small \( \zeta \), we have:

\[
|\Psi\rangle = (1 - \frac{\zeta^2}{2}) |0\rangle + \zeta |1, 1\rangle + \zeta^2 |2, 2\rangle + O(\zeta^3)
\]  

(5)

If \( P_i(I) = |\zeta|^2 \) is the probability of creating one pair per pulse with a pump intensity \( I \) in source i, then the probability of creating 4 photons per pulse in source i by stimulated emission is \( |\zeta|^4 = P_i^2(I) \). The probability of simultaneously creating one pair in each crystal is \( P_1(I) P_2(I) \). Assuming that \( P_1(I) = P_2(I) \) the 4-photons state can then be written as follows (not normalized):

\[
|\Psi_{4\text{ph}}\rangle = |2_1, 0_2\rangle_A |2_1, 0_2\rangle_B \\
+ |1_1, 1_2\rangle_A |1_1, 1_2\rangle_B \\
+ |0_1, 2_2\rangle_A |0_1, 2_2\rangle_B
\]  

(6)

where here for instance \( |n_1, m_2\rangle_A \) means that we have \( n \) photons in source 1 and \( m \) photons in source 2 created in the PDC mode A. It is important to notice that, due to stimulated emission, the amplitudes of each of the 3 terms are the same. This means that, the probability of creating 4 photons per pulse in a specific source is the same as the probability of creating simultaneously 2 photons in source 1 and 2 photons in source 2.

If there is no interference, the photons arriving at the beam splitter will split in half of the cases. The probability of detecting a coincidence outside the dip (od) is the probability of creating 4 photons per pulse in a specific source. The first two terms represent the creation of four photon in either source, the last term the creation of one pair per source. Inside the dip (id), the contribution of the events where one pair per source is created drops to zero (Eq. 2). We thus have:

\[
P_{\text{id}} \propto \left( \frac{P_1^2}{2} + \frac{P_2^2}{2} + \frac{P_1 P_2}{2} \right) = \frac{3 P^2}{2}
\]  

(7)

Finally, the visibility is:

\[
V = \frac{P_{\text{id}} - P_{\text{od}}}{P_{\text{od}}} = \frac{3 P^2 - 2 P^2}{3 P^2} = \frac{1}{3}
\]  

(9)

The maximum theoretical visibility is thus \( V = 33\% \), because, in this case, we cannot discard the events where both photon pairs are created in the same crystal. Note that this demonstrate 2 photon interference between 2 thermal sources [19] [20] [21]. However if we detect the two remaining photons as well (4-photon coincidences), we post-select only the events where we create one photon pair per crystal. Therefore the maximum theoretical visibility is \( V = 100\% \). A detailed theoretical analysis can be found in [21]. Obviously, this is valid only if we can neglect the probability of creating three pairs at the same time, two in one source and one in the other one. We will discuss this case later.

### III. EXPERIMENTAL SETUP

The experimental setup is shown in figure [1]. The pump laser is a Ti-Sapphire mode-locked laser (Coherent Mira),
operating at a wavelength of 710 nm and generating 150 femto-second pulses with 4.5 nm bandwidth (FWHM). The pump beam is split by a beam splitter (BS 1), and the two output modes are used to pump two 10 mm Lithium Triborate (LBO) non linear crystals. The average pump power is $P_{\text{pump}} \approx 40 \text{ mW}$ per crystal. In each crystal, non-degenerate collinear photons pairs at telecom wavelength (1310 nm/1550 nm) are produced by type I parametric down conversion. The photons are then coupled into a standard optical fiber and separated using a wavelength division multiplexer (WDM). The 1310 nm photons are directed to a 50/50 fiber coupler (BS 2). The length of optical fibers before the beam-splitter is equalized within a few hundreds of $\mu$m, in order to have the same chromatic dispersion in the two input modes. To ensure equal polarization for the photons coming from either source, we use a fiber optical polarization controller (PC) inserted in one arm. In order to insure temporal indistinguishability, the optical distance between BS1 and BS2 must be the same within the coherence length of the down converted photons. To vary this distance and hence to vary the temporal overlap, we use the retroreflector R that is mounted on a micrometric translation stage.

The photons are detected with photon counters. One output of BS 2 is connected to a passively quenched Germanium avalanche photodiode (Ge APD) cooled with liquid nitrogen. The quantum efficiency of The Ge APD is 10% for 40 kHz dark counts. The dark counts are reduced to around 3 kHz by making a coincidence with a 1 ns clock signal delivered simultaneously with each laser pulse ($t_0$). The signal count rate on the Ge APD is 40 kHz. The other output is connected to a Peltier cooled (T=220K) Indium Gallium Arsenide (InGaAs) APD, operating in so-called gated mode [7]. This means that it is only activated within a short time window (100 ns) after a Ge-$t_0$ coincidence. InGaAs APDs feature a quantum efficiency of around 30% for a dark count probability of $\approx 10^{-4}$ per ns. Interference filters (IF) (10 nm FWHM centered at 1310 nm) are placed in front of the detectors to increase the coherence length (time) of the down converted photons to 75 $\mu$m (250 fs). Using the side peaks method developed in [22], we measure the probability to create one photon pair per pulse in the spectral range given by the filters to be of around 4%. The signals from the APD’s are finally sent to detection and fast (1 ns) coincidence electronics. A coincidence between the two detectors for 1310 nm photons and the laser clock ($t_0$) is referred as a 3-fold coincidence.

In order to obtain a Mandel dip with 100% visibility, a 4-photon coincidence using also the two others photons at 1550 nm is necessary, in order to post-select only the interfering events. The photons at 1550 nm are detected with InGaAs APDs, gated using a 3-fold coincidence (2 photons at 1310 nm + $t_0$). We thus speak of 5-fold coincidence in this case. The very low gate rate imposed by this scheme allows us to avoid problems with afterpulses of the InGaAs APDs [7]. Interference filters (10 nm FWHM centered at 1550 nm) are also placed in front of the 1550 nm detectors, in order to reduce the probability of detecting events where 3 pairs are created simultaneously.

IV. RESULTS

Figure 2 shows the coincidence count rate as a function of the position of the retroreflector R, i.e. of the delay of one photon. The circles represent the 3-fold coincidences (2 photons at 1310 nm + $t_0$) and the squares the 5-fold coincidences (4 photons +$t_0$). We measure around 160 net 3-fold coincidences and around 0.06 net 5-fold coincidences per second outside the dip. Accidental coincidences (around 20 3-fold and 0.015 5-fold coincidences per second) are already subtracted in the presented data. 3 fold coincidences slightly vary ($\approx 10\%$), probably due to temperature variation in the lab during day time measurement, and are normalized with the square of single count rate of the Ge APD. The 5-fold curve has been measured during the night, when the temperature was more stable. Thus, count rates variations were smaller and raw data can be used without normalization.

The shape of the dip is given by the convolution of the two wave-packets arriving at the beam splitter [8]. The spectral transmission of the IF has been measured to be well approximated by a gaussian. We thus fitted our data with the following function:

$$R_c(\tau) = S \left(1 - Ve^{-\frac{2\tau^2}{\sigma^2}}\right)$$

(10)

where $S$ is the number of coincidences outside the dip, $V$ the visibility, $\tau$ the optical delay and $\sigma$, the $1/\sqrt{\pi}$ half width of the gaussian function. Due to the convolution product, the expected FWHM of the dip is $\sqrt{2c}$, where $c$ is the FWHM coherence length of the down converted photons, given by the IF.

We obtain a raw (i.e without subtracting accidental coincidence) visibility of $V = (21 \pm 1\%)$ for the 3-fold coincidence. When subtracting accidental coincidence, it increases to $V = (28 \pm 2\%)$, which is close to the theoretical visibility of 39%. The FWHM of the gaussian fit is
of $142 \pm 15 \mu m$. This is slightly larger than the expected value ($\sqrt{2}l_c = 107 \mu m$ for 10nm IF at 1310 nm). When fitting the 5-fold coincidence curve, we obtain a raw visibility of $(77 \pm 2.5)\%$, which increases to $(84 \pm 2.5)\%$ when subtracting accidental coincidences. The FWHM of the gaussian fit is larger for the 5-fold coincidence curve. This can be qualitatively understood by the fact that the 10 nm IF at 1550 nm reduces the bandwidth of the 1310 twin photons to $\approx 7 \text{ nm}$ by energy conservation. Various reasons could explain the difference between the theoretical and experimental visibilities. The main reason is the probability of detecting events where 3 pairs are created simultaneously, 2 in one source and 1 in the other source. A calculation similar to eq 9, starting from an input state $|\psi_{in}\rangle = \frac{1}{\sqrt{2}} (a^\dagger)^2 b^\dagger |0\rangle$ shows that these events will indeed induce spurious coincidences and thus reduce the visibility of the dip. To estimate this maximal visibility, we calculate the maximal and minimal coincidence count rates ($I_{\text{max}}$ and $I_{\text{min}}$) for all cases leading to a 5-fold coincidence, and insert them into eq. 10 with the corresponding probabilities, computed from eq 11. We neglect the events where more than 3 pairs are created simultaneously. The finite quantum efficiency $\eta$ of detectors is taken into account, in the sense that the probability of having a click when two photons arrive at the detector is $2\eta - \eta^2 \approx 2\eta$ for small $\eta$. In the case where the transmissions of the two inputs modes of the beam splitter are the same, a simple but lengthy calculation leads to:

$$V_{\text{max}} = \frac{1 + 8P}{1 + 12P},$$

where $P$ is the probability of creating one pair per pulse. For $P = 4\%$, we find $V_{\text{max}} = 89\%$.

Furthermore, even in the events where we have one photon per input mode, the following reasons, listed by order of importance, might induce distinguishability between the photons, and thus diminish the visibility of the dip: There might be remaining temporal distinguishability due to relatively large (10 nm) filtering of the downconverted photons (compared to the pump bandwidth)\cite{21}. Moreover, a slight difference in the polarization of the two photons when arriving at the beam splitter could result in a which-path information. Finally, different phase-matching conditions in the two crystals could result in photon pairs with different spectra. Those difference might not be completely cancelled with the 10 nm interference filters.

V. CONCLUSION

We observed quantum interference with photon pairs at telecommunication wavelengths created by parametric down conversion in spatially separated sources. Two photons, one from each source were mixed on a beam splitter. When recording 2 photon coincidences and varying the temporal overlap between the two photons, we observed a Mandel-type dip with visibility of $(28 \pm 2)\%$. This is close to the maximum visibility of 33\%, limited by the impossibility to discard the events where 2 pairs are created in the same crystal. Recording 4 photon coincidences and thus post-selecting only events where at least one pair is created in each source, we obtained a net visibility of $(84 \pm 2.5)\%$, close to the theoretical value. This experiment constitutes a first step towards the realization of quantum teleportation and entanglement swapping with independent sources. However, note that truly independent sources require the use of independent but synchronized fs laser. Although this is nowadays commercially available\cite{22}, synchronization of two fs laser at large distance still has to be demonstrated.

*Note* It was recently brought to our attention that a similar experiment was reported in the conference QELS 99 by Rhee and Wang\cite{24}.

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FIG. 2: Coincidences count rate as a function of the delay of one photon. The circles are 3-fold coincidences (2 photons + laser clock) and the squares are 5-fold coincidences (4-photon + laser clock). The net visibility of the dip is 28\% and 84\% respectively. The integration time for 3-fold coincidence is 200 s, while for 5-fold coincidence, it varied from 30 to 60 min, such that the statistical error on the counts is around 10\%. The 5-fold rate is scaled to 200 s.
[1] R.P. Feynman, Lectures on physics, vol.3, Addison-Wesley
[2] D.M. Greenberger, M.A. Horne and A. Zeilinger, Physics Today, August 1993, p. 22
[3] C.K. Hong, Z.Y. Ou, and L. Mandel, Phys. Rev. Lett. 59, 2044-2046 (1987)
[4] W. Tittel and G. Weihs, Quantum Information and Computation 1, 3-56 (2001)
[5] M. Michler, K. Mattle, H. Weinfurter and A. Zeilinger, Phys. Rev. A 53, 1209 (1996)
[6] M. Zukowski, A. Zeilinger and H. Weinfurter, Ann. NY Acad. Sci. 775, 91-102 (1995)
[7] D. Stucki, G. Ribordy, A. Stefanov, H. Zbinden, J.G. Rarity, and T. Wall, J. of Mod. Optics, 48 (13), 1967-1982 (2001).
[8] Z.Y. Ou and Y.J. Lu, Phys. Rev. Lett. 83 2556 (1999)
[9] J.G. Rarity, P.R. Tapster, R. Loudon, in in Quantum Interferometry, edited by F. De Martini, G. Denardo, and Y. Shih (VCH, Weinheim, 1996), pp. 211, quant-ph/9702032
[10] D. Bouwmeester, J.W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, Nature 390 575 (1997)
[11] J. Pan, D. Bouwmeester, H. Weinfurter and A. Zeilinger, Phys. Rev. Lett. 80, 3891 (1998)
[12] T. Jennewein, G. Weihs, J. Pan, and A. Zeilinger, Phys. Rev. Lett. 88, 017903 (2002)
[13] D. Bouwmeester, J. Pan, M. Daniell, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. 82, 1345 (1999)
[14] J. Pan, M. Daniell, S. Gasparoni, G. Weihs, and A. Zeilinger, Phys. Rev. Lett. 86, 4435 (2001)
[15] H.-J. Briegel, W. Dr. J. I. Cirac, and P. Zoller, Phys. Rev. Lett. 81, 5932-5935 (1998)
[16] A. Lamas-Linares, J.C. Howell and D. Bouwmeester, Nature 412 887-890 (2001)
[17] D.F. Walls, G.J. Milburn, Quantum optics (Springer-Verlag, Berlin, 1994), Chap.5
[18] V. Scarani et al, in preparation
[19] L. Mandel, Phys. Rev. A 28, 929-943 (1983)
[20] S.J. Kuo, D.T. Smithey and M.G. Raymer, Phys. Rev. A 43, 4083-4086 (1991)
[21] Z.Y. Ou, J.-K. Rhee and L.J. Wang, Phys. Rev. A 60, 5933-5936 (1999)
[22] I. Marcikic, H. de Riedmatten, W. Tittel, V. Scarani, H. Zbinden and N. Gisin, Phys. Rev. A 66, 062308 (2002)
[23] www.menlosystems.de
[24] J.-K. Rhee and L.J. Wang, proceedings of QELS 99