

**Quantum interference with photon pairs created in spatially separated sources**H. de Riedmatten,<sup>1</sup> I. Marcikic,<sup>1</sup> W. Tittel,<sup>1,2</sup> H. Zbinden,<sup>1</sup> and N. Gisin<sup>1</sup><sup>1</sup>*Group of Applied Physics-Optique, University of Geneva, Geneva, Switzerland*<sup>2</sup>*Danish Quantum Optics Center, Institute for Physics and Astronomy, University of Aarhus, Aarhus, Denmark*

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We report on a quantum interference experiment to probe the coherence between two photons coming from nondegenerate 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.

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**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 [1,2]. In addition to the most well-known single-photon or first-order interference, interference in the coincidence detection of two or more photons can also be observed. The so-called second-order or two-photon interference has been used to highlight the bosonic nature of photons [3] and to demonstrate nonlocal effects between photons forming entangled pairs. Moreover, it is at the origin of the new field of quantum information processing (for a recent overview concerning the last two points, see, e.g., Ref. [4]).

Observing the second-order quantum interferences with photons without common history is a very important issue, since this forms the basis of entangling those photons through a so-called interferometric Bell-state measurement [5,6]. The simplest way to observe such interference is to mix the independent, however indistinguishable photons on a beam splitter (i.e., one photon per input mode). In this case, the probability amplitudes of both the photons being transmitted or both reflected cancel each other and the two photons will always be detected in the same output mode. This is valid of course only if the photons coming from the two sources become indistinguishable after the beam splitter, i.e., if they are described by identical polarization, spatial, temporal, and spectral modes. In other words, when all indistinguishability criteria are met, the count rate for coincidence detection of two photons in different output modes of the beam splitter drops to zero. The first experiments showing this effect were made by Mandel and co-workers at the end of 1980s [3]. The drop in the coincidence count rate when varying the temporal overlap between the two photons is often referred to as a “Mandel dip.” In those early experiments, the two photons belonged to one photon pair generated by parametric down-conversion (PDC). In this case, the temporal indistinguishability is ensured by the fact that the two photons are created simultaneously. In cases where two independent photons (i.e., created in different sources or different PDC events) have to interfere, there are two possibili-

ties to restore the temporal indistinguishability (i.e., to ensure that only photons detected in coincidence within their coherence time contribute). The first and most common way is to create the photon pairs using ultrashort pump pulses such that the down-converted photon’s coherence time (given by the phase-matching conditions) is superior to the duration of the pump pulse [6]. The second possibility is to increase the coherence time of the photons such that it becomes larger than the temporal resolution of the detectors. In this way, one can select the photons arriving at the same time at the beam splitter directly by their arrival times at the detectors. This method requires coherence times of the order of a few hundred picoseconds, with current avalanche photodiodes detectors [7]. This can be achieved for instance by using a sub-threshold OPO (optical parametric oscillator) configuration [8].

In the context of observing quantum interference between independent photons, Rarity *et al.* have performed an experiment where a one-photon state obtained by PDC and a weak coherent state were mixed at a beam splitter [9]. More recently, experiments where two photons from different pairs interfere at a beam splitter have been carried out in order to implement quantum teleportation [10], entanglement swapping [11,12], and to create Greenberger-Horne-Zeilinger (GHZ) states [13,14]. In these experiments, however, the two photon pairs were created in the same crystal by means of two subsequent passages of a pump pulse.

In this article, we go a step further and report on the observation of quantum interference with photons from different pairs created in two spatially separated sources. We use non degenerate photon pairs at telecom wavelength. This is an important extension with respect to the previous experiments since some quantum communication protocols (for instance, the quantum repeater [15]) rely on the use of photon pairs created at different locations, hence photon pairs from different sources.

**II. MANDEL DIP WITH INDEPENDENT PDC SOURCES**

As shown in Fig. 1, we create pairs of nondegenerate photons in two nonlinear 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  $d^\dagger$ ) as the creation operators of the two input (output) modes, respectively. Unitar-

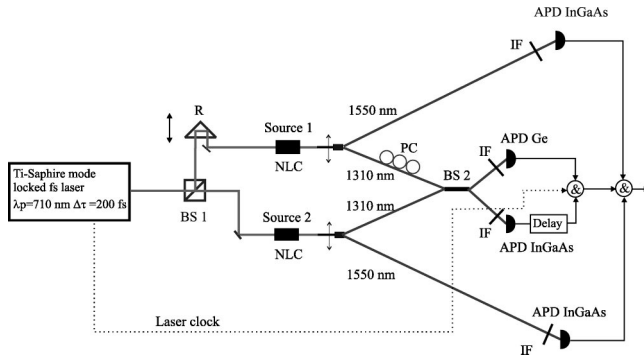


FIG. 1. Experimental setup used to observe quantum interferences with photons coming from different sources.

ity implies that the phase difference between a reflected and a transmitted photon is  $\pi/2$ . For a 50-50 beam splitter, the evolution is thus  $a^\dagger \rightarrow 1/\sqrt{2}(c^\dagger + id^\dagger)$  and  $b^\dagger \rightarrow 1/\sqrt{2}(ic^\dagger + d^\dagger)$ .

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

$$|\psi_{in}\rangle = a^\dagger b^\dagger |0\rangle. \quad (1)$$

After the beam splitter, the state becomes

$$\begin{aligned} |\psi_{out}\rangle &= \frac{1}{2}[i(c^\dagger)^2 + i(d^\dagger)^2 + c^\dagger d^\dagger - c^\dagger d^\dagger]|0\rangle \\ &= i\frac{1}{\sqrt{2}}|2\rangle_c |0\rangle_d + i\frac{1}{\sqrt{2}}|0\rangle_c |2\rangle_d. \end{aligned} \quad (2)$$

We thus find that for a 50-50 beam splitter, the two probabilities 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 lose temporal indistinguishability, and the destructive interference diminishes. We define the visibility of the Mandel dip as follows :

$$V_{dip} = \frac{I_{max} - I_{min}}{I_{max}}. \quad (3)$$

In the case of two PDC sources, there are different possibilities to create two 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 nondegenerate PDC follows the distribution [17,18]:

$$|\Psi\rangle = e^{-g} e^{\Gamma A^\dagger B^\dagger} |0\rangle = \sum_n \frac{(\tanh \zeta)^n}{\cosh \zeta} |n_A, n_B\rangle, \quad (4)$$

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 nonlinear susceptibility  $\chi^{(2)}$ ,  $g = \ln(\cosh \zeta)$  and  $\Gamma = \tanh \zeta$ . In the limit of small  $\zeta$ , we have

$$|\Psi\rangle = \left(1 - \frac{\zeta^2}{2}\right)|0\rangle + \zeta|1,1\rangle + \zeta^2|2,2\rangle + O(\zeta^3). \quad (5)$$

If  $P_i(I) = |\zeta|^2$  is the probability of creating one pair per pulse with a pump intensity  $I$  in source  $i$  ( $i=1,2$ ), then the probability of creating four photons per pulse in source 1 by stimulated emission is  $|\zeta|^4 = P_1^2(I)$ . 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 four photon state can then be written as follows (not normalized):

$$\begin{aligned} |\Psi_{4ph}\rangle &= |2,1,0\rangle_A |2,1,0\rangle_B + |1,1,1\rangle_A |1,1,1\rangle_B \\ &\quad + |0,1,2\rangle_A |0,1,2\rangle_B, \end{aligned} \quad (6)$$

where, 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 three terms are the same. This means that, the probability of creating four photons per pulse in a specific source is the same as the probability of creating simultaneously two photons in source 1 and two 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 thus proportional to

$$P_{od} \propto \left(\frac{P_1^2}{2} + \frac{P_2^2}{2} + \frac{P_1 P_2}{2}\right) = \frac{3P^2}{2}, \quad (7)$$

where  $P_1 = P_2 = P$  is the probability of creating one pair per pulse per source. The first two terms represent the creation of four photons in either source, and the last term represents 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

$$P_{id} \propto \left(\frac{P_1^2}{2} + \frac{P_2^2}{2} + 0\right) = P^2. \quad (8)$$

Finally, the visibility is

$$V = \frac{P_{od} - P_{id}}{P_{od}} = \frac{3P^2 - 2P^2}{3P^2} = \frac{1}{3}. \quad (9)$$

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 demonstrates two-photon interference between two thermal sources [19–21]. However, if we detect the two remaining photons as well (four-photon coincidences), we postselect 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 Ref. [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 Fig. 1. The pump laser is a Ti:sapphire mode-locked laser (Coherent Mira), operating at a wavelength of 710 nm and generating 150-fs pulses with 4.5 nm bandwidth (full width at half maximum, 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) nonlinear crystals. The average pump power is  $\bar{P}_{pump} \approx 40$  mW per crystal. In each crystal, nondegenerate collinear photons pairs at telecom wavelength (1310 nm and 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. 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 micrometer, 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 ensure 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 ( $T=220$  K) indium-gallium-arsenide  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  APD, operating in so-called gated mode [7]. This means that it is only activated within a short-time window (100 ns) after a  $\text{Ge}-t_0$  coincidence.  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  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  $75 \mu\text{m}$  (250 fs). Using the side-peaks method developed in Ref. [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 APDs 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 threefold coincidence.

In order to obtain a Mandel dip with 100% visibility, a four-photon coincidence using also the two other photons at

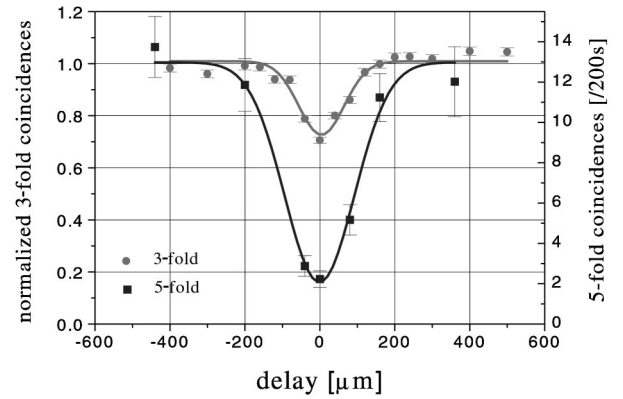


FIG. 2. Coincidences count rate as a function of the delay of one photon. The circles are threefold coincidences (two photons + laser clock) and the squares are fivefold coincidences (four-photon + laser clock). The net visibility of the dip is 28% and 84%, respectively. The integration time for threefold coincidence is 200 s, while for fivefold coincidence, it varied from 30 to 60 min, such that the statistical error on the counts is around 10%. The fivefold rate is scaled to 200 s.

1550 nm is necessary, in order to postselect only the interfering events. The photons at 1550 nm are detected with  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  APDs, gated using a threefold coincidence (two photons at 1310 nm +  $t_0$ ). We thus speak of fivefold coincidence in this case. The very low gate rate imposed by this scheme allows us to avoid problems with after pulses of the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  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 three 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 threefold coincidences (two photons at 1310 nm +  $t_0$ ) and the squares the fivefold coincidences (four photons +  $t_0$ ). We measure around 160 net threefold coincidences and around 0.06 net fivefold coincidences per second outside the dip. Accidental coincidences (around 20 threefold and 0.015 fivefold coincidences per second) are already subtracted in the presented data. Threefold 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 fivefold curve has been measured during the night, when the temperature was more stable. Thus, count rate 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 [3]. 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 :

$$R_c(\tau) = S(1 - Ve^{-\tau^2/2\sigma_\tau^2}), \quad (10)$$



where  $S$  is the number of coincidences outside the dip,  $V$  the visibility,  $\tau$  the optical delay, and  $\sigma_\tau$  the  $1/\sqrt{e}$  half width of the Gaussian function. Due to the convolution product, the expected FWHM of the dip is  $\sqrt{2}l_c$ , where  $l_c$  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 threefold coincidence. When subtracting accidental coincidence, it increases to  $V=(28\pm 2)\%$ , which is close to the theoretical visibility of 33%. The FWHM of the Gaussian fit is of  $142\pm 15\ \mu\text{m}$ . This is slightly larger than the expected value ( $\sqrt{2}l_c=107\ \mu\text{m}$  for 10-nm IF at 1310 nm). When fitting the fivefold 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 ( $222\pm 25\ \mu\text{m}$ ) is larger than for the threefold 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 three pairs are created simultaneously, two in one source and one in the other source. A calculation similar to Eq. (2), starting from an input state  $|\psi_{in}\rangle = 1/\sqrt{2}(a^\dagger)^2 b^\dagger|0\rangle$  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 ( $I_{max}$  and  $I_{min}$ ) for all cases leading to a fivefold coincidence, and insert them into Eq. (3) with the corresponding probabilities, computed from Eq. (4). We neglect the events where more than three 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

$$V_{max} = \frac{1+8P}{1+12P}, \quad (11)$$

where  $P$  is the probability of creating one pair per pulse. For  $P=4\%$ , we find  $V_{max}=89\%$ . Furthermore, even in the events where we have one photon per input mode, the fol-

lowing 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 down-converted photons (compared to the pump bandwidth) [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 differences might not be completely canceled 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 two 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 two pairs are created in the same crystal. Recording four-photon coincidences and thus postselecting 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 step towards the realization of quantum teleportation and entanglement swapping with independent sources. However, note that the truly independent sources require the use of independent but synchronized femtosecond laser. Although, this is nowadays commercially available [23], synchronization of two femtosecond lasers at large distance still has to be demonstrated.

*Note added.* It recently was brought to our attention that a similar experiment was reported in the conference QELS 99 by Rhee and Wang [24].

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