Experimental realization of a measurement conditional unitary operation at single photon level and application to detector characterization.

M. Genovese, G. Brida, M. Gramegna, and M.L. Rastello  
Istituto Elettrotecnico Nazionale Galileo Ferraris, Strada delle Cacce 91, 10135 Torino, Italy

M. Chekhova, L. Krivitsky, and S. Kulik  
Phys. Dep., M.V. Lomonosov Moscow State Univ., 119992 Moscow, Russia.

Our last experimental results on the realization of a measurement-conditional unitary operation at single photon level are presented. This gate operates by rotating by 90° the polarization of a photon produced by means of Type-II Parametric Down Conversion conditional to a polarization measurement on the correlated photon. We then propose a new scheme for measuring the quantum efficiency of a single photon detection apparatus by using this set-up. We present experimental results obtained with this scheme compared with traditional biphoton calibration. Our results show the interesting potentiality of the suggested scheme.

I. INTRODUCTION

The possibility of performing a unitary transformation on a qubit conditionally on the result of the measurement on another one is a fundamental tool for Quantum Information [1]. For example, in teleportation protocols [2], teleportation is obtained by Bob doing an opportune unitary transformation on its sub-part of an entangled system after having received classical information on the result of a Bell measurement performed by Alice on her sub-part of the entangled system and the unknown state to be teleported. Similarly, in entanglement swapping protocols a joint measurement of two members of two distinct entangled pairs allows, by means of conditional unitary transformation, to create a desired entangled state between the two surviving members.

Nevertheless, in most of experiments realized up to now with single photons both for teleportation [3] and swapping [4], this part of the protocol was not accomplished, and only correlation measurements with a fixed polarization selection were obtained. The only exception is Ref. [5], where a Pockels cell was used for conditional transformations in an active teleportation protocol. Conditional transformations were also performed in experiments where one of the photons of an entangled pair triggered polarization rotation on the other one, to increase the efficiency of the parity check [6] and to produce signal photons on 'pseudodemand', i.e., in a given time interval after the trigger detection event [7].

In this paper we present the realization of a set-up addressed to perform conditional unitary transformations on the polarization state of a photon belonging to a polarization-entangled pair. This experiment is the first demonstration of 'purifying' the polarization state of a photon that is initially prepared in a mixed polarization state (initial degree of polarization is equal to zero). As a result of transformations, the degree of polarization increases; its final value is given by the quantum efficiency of the 'trigger' detector. Due to this fact, one can notice another important advantage of our experiment: it can be used for the absolute calibration of photodetectors (absolute measurement of quantum efficiency), a property with large interest for various applications. In fact, in the recent years single photon detectors have found various important scientific and technological applications, which demand for a precise determination of the quantum efficiency of these apparatuses. Among them the studies about foundations of quantum mechanics [8] (and in particular Bell Inequalities measurements [9, 12]), quantum cryptography [10], quantum computation [11], etc.

Classical calibration schemes are based on the use of a strongly attenuated source whose (unattenuated) intensity has been measured by means of a radiometer. The precision of this kind of measurement is limited by the uncertainty in the calibration of the high insertion loss required for reaching single photon level.

An alternative is offered by the use of photons produced by means of parametric down conversion (PDC). These states have the property that photons are emitted in pairs strongly correlated in direction, wavelength and polarization. Furthermore, photon of the same pair are emitted within tens of femtoseconds. Since the observation of a photon on a certain direction (signal) implies the presence of another on the conjugated direction (idler), if this last is not observed this depends on the non-ideal quantum efficiency of the detector, which can be measured in this way [13, 14]. This method is now approaching a metrological level.

A comparison between this last scheme and our new one will be presented in the following.
II. DESCRIPTION OF THE MEASUREMENT-CONDITIONED UNITARY GATE

Our scheme consists in measuring the polarization of a photon belonging to a polarization entangled pair and to perform a unitary operation, by means of a Pockels cell, on the second member of the pair conditional to the result of this measurement.

In order to realize this setup, first of all one needs to produce polarization entangled states of photons by using parametric fluorescence.

This state can be generated either by using type-II PDC \[9\] or the superposition of two type I PDC emissions \[12\], obtaining the Bell state:

\[
\left| \psi^+ \right> = \frac{\left| H \right> \left| V \right> + \left| V \right> \left| H \right>}{\sqrt{2}} \tag{1}
\]

where \( H, V \) denote horizontal and vertical polarization respectively (other phases between the two components can also be obtained).

Then, one of the photons of the pair is addressed, after a polarization selection, to a first detector.

When this photon (signal) is detected, we modify the polarization of the delayed second photon (idler) of the pair by means of a Pockels cell driven by a high voltage supply controlled by the output of the first detector.

In particular a rotation of 90° of the polarization of the second photon can be produced after the first photon is detected after a specific polarization selection. This realizes the desired measurement-conditional unitary transformation.

The result of this unitary operation is that the state of the idler photon, which was initially mixed, becomes partly purified due to this transformation. In terms of polarization properties, light became partly polarized (polarization degree became equal to the quantum efficiency of the trigger detector) while initially it was completely non-polarized (polarization degree was zero).

It is worth mentioning that variation of the polarization degree, which we realize in our experiment, is impossible by means of only linear lossless optical methods \[17\]. However, in the present experiment, the transformation performed over the signal photon is essentially nonlinear since it is triggered by the detection of the idler photon entangled to this photon.

On the other hand, it must be noticed that in this way the final polarization state of the second photon depends on the quantum efficiency of the first detector, since the Pockels cell is activated only when the first photon is effectively detected. This property, representing a limit for the operation of the measurement-conditional unitary gate, gives nevertheless the opportunity for realizing an innovative scheme for absolute calibration of single-photon detectors, which will be discussed below.

III. EXPERIMENTAL REALIZATION OF THE MEASUREMENT-CONDITIONAL UNITARY GATE

In our setup (see Fig. 1,2) we have generated biphoton states by pumping with an argon laser at 351 nm a BBO crystal (5x5x5 mm) cut for producing type II Parametric Down Conversion. Residual pump beam after passing through the non-linear crystal was absorbed by a beam dumper. Then we have selected the directions where the vertically polarized and horizontally polarized emitted circles, corresponding to both photons having a 702 nm wavelength, intersect. A quartz crystal follows the BBO crystal in order to compensate the walk-off of ordinary and extraordinary rays due to birefringence in BBO. In this way indistinguishability between the two polarizations is restored generating the Bell state of Eq. 1.

After crossing a polarizing beam splitter (PBS) the first (signal) photon was detected by means of a Perkin-Elmer single photon detector preceded by a pinhole and a red filter. The second photon (idler) was delayed by 200 m of optical fiber. Input and output fiber coupling were realized with 20x objectives with a 0.4 numerical aperture. At the output of the fiber this photon was then addressed to a KDP Pockels cell (supplied at 5.2 kV) followed by a Glan-Thompson polarizer, an interference filter at 702 nm (4 nm FWHM) and a second Perkin-Elmer Silicon avalanche single photon detector.

When the Pockels cell is not active the reduced polarization density matrix of the second photon corresponds to a completely unpolarized case. In fact, the observed intensity of the signal measured when varying the setting of the Glan-Thompson polarizer is flat (see Fig. 3).

On the other hand, when the Pockels cell is active the system realizes a rotation of the polarization of the second photon conditioned to a polarization measurement on the conjugated arm. If we choose to perform a rotation by 90° in the same basis of the polarization measurement of the first photon, the result is a purification of the polarization state of the second one.
Our experimental results at coincidence level are shown in Fig. 4 in the case where we choose the $45^\circ - 135^\circ$ basis both for polarization measurement and polarization rotation (further results will be presented in a following paragraph when discussing detector calibration). In this basis the state is
\[ |\phi^- \rangle = \frac{|45\rangle|45\rangle - |135\rangle|135\rangle}{\sqrt{2}} \] (2)

As expected for an entangled state the maximum of coincidences is shifted of $90^\circ$ when the Pockels cell is active: when the first detector is preceded by a polarizer at $-45^\circ$ the maximum of coincidences is when the polarizer before the second detector is set at $135^\circ$ with the Pockels cell off and at $45^\circ$ with the Pockels cell on. The visibility is 87.2 % when the Pockels cell is off and 86.3 % when it is on.

**IV. DESCRIPTION OF THE METHOD FOR CALIBRATING SINGLE PHOTON DETECTORS.**

This scheme for realizing a measurement conditional unitary gate can be applied to the calibration of single photon detectors. The method is based on the fact that in the real situation the efficiency $\eta_1$ of the first detector is smaller than unity and thus only a fraction of incident photons will be observed and produce an effect on the Pockels cell. Therefore the final density matrix for the second photon does not correspond to the pure state:
\[ \rho = |V\rangle\langle V| \] (3)
but to a mixed one:
\[ \rho = 1/2[(1 + \eta_1)|V\rangle\langle V| + (1 - \eta_1)|H\rangle\langle H|] \] (4)
which depends on the quantum efficiency $\eta_1$ of the first detector, allowing a calibration of it. If we insert a polarizer in front of the second detector (Fig. 1) and vary its angle $\theta$ (with respect to the horizontal axis), the count rate $N_2$ of the second detector will be given by:
\[ N_2 = N_0 \cdot \alpha \eta_2 [1 - \eta_1 \cos(2\theta)] \] (5)
where $\alpha$ represents the idler optical path loss (fiber and Pockels cell transmittances), $\eta_2$ is the quantum efficiency of the second detector and $N_0$ the rate of emission of entangled pairs.

The visibility $V$ of the signal counting rate $N_2$ obtained by rotating the polarizer (G) preceding the second detector does not depend on the quantum efficiency $\eta_2$ while it is directly determined by the value of $\eta_1$,
\[ V = \frac{N_2^V - N_2^H}{N_2^V + N_2^H} = \eta_1 \] (6)
representing therefore a measurement of this ($N_2^H$ and $N_2^V$ are the counts on the second detector when the polarizer is set at $0^\circ$ and $90^\circ$ respectively). No coincidence measurement is, in principle, necessary.

Incidentally, this effect can be also described in terms of the Stokes parameters, which are initially $S_0 = N$, $S_1 = S_2 = S_3 = 0$, where $N$ is the photon number, but become, as a result of transformation, $S_0 = N$, $S_1 = \eta_1 N$, $S_2 = S_3 = 0$. From the Stokes parameters, one can find the polarization degree, which is standardly defined as
\[ P = \sqrt{S_1^2 + S_2^2 + S_3^2} / S_0 \] (7).

We see that without the transformation, $P = 0$ and in the presence of the transformation, $P = \eta_1$.

The same effect can also be described in terms of the von Neumann entropy $S$, whose value characterizes the purity of a state, going from zero for a pure state to unity for a completely mixed one. In our case, if $\eta_1 = 1$ the final polarization reduced density matrix $\rho_2$ of the second photon, corresponding to a pure state, gives $S(\rho_2) = 0$. On the other hand if $\eta_1 = 0$ the final polarization reduced density matrix of the second photon is completely mixed with $S(\rho_2) = 1$. Intermediate cases lie between these two values (see Fig. 5).
The set-up of the calibration scheme is substantially identical to the one presented in section 3, only the idler photon is in this case delayed by 50 m of single mode (4 μm core) polarization maintaining fiber. The detection apparatus driving the Pockels cell (including filters and iris) is the device under calibration. Nevertheless, in this case one does not need to have an entangled state and the quartz crystal compensator is not necessary. Therefore, for no compensator introduced the produced state is a mixed one:

\[ \rho = \frac{|HV\rangle \langle HV| + |VH\rangle \langle VH|}{2} \]  

(8)

Measurements are performed in the 0° – 90° basis.

As before, when the Pockels cell in not activated the polarization degree of the second photon is zero. When the Pockels cell is active the system realizes a rotation of 90° on the polarization of the second photon conditioned to a measurement of a vertically polarized photon on the conjugated arm. The results of our measurement under this condition are shown in Fig. 6 and 7. When the cell is active the measured signal has a (1 + \(\eta \cos(2\theta)\)) behaviour as a function of the polarizer setting \(\theta\). When the background, estimated by rotating of 90° the pump laser polarization, is subtracted the data show a (36.8 ± 2.4)% visibility.

This result represents a rough measurement of the quantum efficiency that must be corrected for dead time of the system and the efficiency of the Pockels cell.

The Pockels cell driver, when triggered by detector under calibration, generates a high-voltage pulse with fast rising edge (5 ns), a 100 ns flat-top and a long fall tail of about 3.5 μs duration (Fig.8). When the mean trigger rate exceeds \(10^3\) counts per second the Pockels cell driver is disabled for 1 s. in order to make negligible this effect the counting rate on the detector under calibration must be kept lower than the rate threshold of 10 kHz.

For the sake of completeness in Fig.9 we show the single counts on the second detector for horizontal and vertical polarizations in function of the delay and in Fig. 10 the same for coincidences. It is clearly seen as the polarization of second photon is dominantly vertical when the Pockels cell is on, whilst the two polarization are equivalent, at single-count level, when the delay is too large, so that the photon is received before the Pockels cell has been activated. At coincidence level, when the Pockels cell is activated, coincidences are observed for a vertical polarization. When the delay is increased, the situation is reversed and coincidence between vertically (first detector) and horizontally polarized (second detector) photons is observed.

The effect of a finite efficiency of the Pockels cell apparatus can be precisely estimated by measuring the visibility at coincidence level (Fig.4). In fact in coincidences the effect of the quantum efficiency of the detector under calibration is irrelevant and the reduction of visibility is completely due to the non-ideal Pockels cell apparatus. From the visibility at coincidence level the efficiency of the Pockels cell apparatus can be estimated to be 0.832 ± 0.0023 (see Fig.3). When this further correction is introduced we have

\[ \eta = \frac{N_V - N_H}{N_V + N_H} \cdot \frac{N_V + N_H}{N_V - N_H} \]  

(9)

where \(N_H\) and \(N_V\) are the counts on the second detector when the polarizer is set at 0° and 90° respectively and \(N'_H\) and \(N'_V\) the corresponding coincidence counts. From our data the measured quantum efficiency of the detection apparatus is then 0.441 ± 0.045.

The uncertainties propagation formula can be written as

\[ u^2(\eta) = c_1^2 u^2(N_H) + c_2^2 u^2(N_V) + c_3^2 u^2(N'_H) + c_4^2 u^2(N'_V) \]  

(10)

where \(u\) are the uncertainties and the sensitivity coefficients \(c_i\) are evaluated by standard propagation of uncertainties method.

A summary of the uncertainty budget is given in Table 1.

| Quantity | Value | Standard Deviation | Type of Distribution | Sensitivity Coefficient | Uncertainty contribution |
|----------|-------|--------------------|----------------------|------------------------|-------------------------|
| \(N_H\) | 7.03  | 4.2                | Gaussian             | -0.00067/63            | 0.02840                 |
| \(N_V\) | 16.9  | 5.7                | Gaussian             | 0.003123               | 0.01780                 |
| \(N'_H\)| 4.4   | 1.6                | Gaussian             | 0.01827                | 0.02925                 |
| \(N'_V\)| 48.7  | 2.6                | Gaussian             | -0.00165               | 0.00429                 |

TABLE I: Uncertainty budget for single photon detector calibration with the proposed scheme. Counts are per second.
Finally, in order to compare with other calibration techniques, it is worth introducing a further correction due to losses in polarizer cube. When this correction is made ($\epsilon = 0.9842$) the final result is $\eta_1 = 0.448 \pm 0.045$ (if the correction for a small drift of the pump power shift is made by taking into account the change in the signal counts, the result becomes $0.454 \pm 0.032$). Incidentally, even a better precision can be obtained by using a least square fit method applied to the data presented in Fig.6, which leads to $\eta_1 = 0.486 \pm 0.011$.

For the sake of clarity, it must be emphasized again that the reported quantum efficiency is not the "naked" detector one, but the one corresponding to the detection apparatus including spatial and spectral filtering. In many experimental situations this is the datum necessary for understanding the performances of the set-up. If one wants to measure the "naked" detector quantum efficiency it would be necessary to introduce a corrective factor keeping into account losses in the other elements in the detection apparatus and in the non-linear crystal (corrections are of course needed also for the other calibration method based on PDC). This evaluation is beyond the purposes of this proof-of-principle experiment.

Incidentally, for the sake of completeness, we would like to report that similar results ($\eta = 0.417 \pm 0.024$), albeit less accurate (even if a smaller statistical uncertainty) due to a low efficiency of the Pockels cell, were also obtained by using a Lithium Iodate Pockels cell.

VI. COMPARISON WITH THE TRADITIONAL CALIBRATION SCHEME WITH BIPHOTONS

In order to check the result obtained with the new scheme, we have compared it with the traditional scheme of single photon detector calibration by using biphotons.

In more detail, this procedure [13, 14] consists of placing a couple of photon counting detectors down-stream to the non-linear crystal, along the direction of propagation of correlated photon pairs for a selected couple of frequencies: the detection of an event on one detector guarantees with certainty, thanks to the PDC biphotons properties, the presence of a photon on the conjugated direction with a determined wavelength. If $N$ is the total number of photon pairs emitted from the crystal in a given time interval $T_{\text{gate}}$ and $N_{\text{signal}}$, $N_{\text{idler}}$ and $N_{\text{coincidence}}$ are the mean number of events recorded, in the same time interval $T_{\text{gate}}$, by signal detector, idler detector and in coincidence, respectively, we have the following obvious relationships:

\[
N_{\text{signal}} = \eta_{\text{signal}}N = \eta_{\text{idler}}N
\]

where $\eta_{\text{signal}}$ and $\eta_{\text{idler}}$ are the detection efficiencies on signal and idler arms. The number of events in coincidence is

\[
N_{\text{coincidence}} = \eta_{\text{signal}}\eta_{\text{idler}}N
\]

due to the statistical independence of the two detectors. Then the detection efficiency $\eta_{\text{signal}}$ follows:

\[
\eta_{\text{signal}} = N_{\text{coincidence}}/N_{\text{idler}}
\]

This simple relation, slightly modified by taking into account background subtraction and corrections for acquisition apparatuses [15], is the base for the scheme for absolute calibration of single photon detectors by means of PDC light, which reaches now measurement uncertainty competitive with traditional methods [14, 15].

When we have applied this scheme to the same configuration as described in the previous paragraph, our result has been $\eta = 0.4812 \pm 0.0015$, which includes the corrections [15] for detector dead time ($\tau = 40\text{ns}$) $\gamma = 1 - N_{\text{signal}}\tau$ and for the delay between start and stop signal in Time to Amplitude Converter ($T = 9.3\text{ns}$) $\alpha = 1 - N_{\text{signal}}T$. The data from which this result is derived are shown in Fig.6 in function of the counts on the detector under calibration (varied by varying the power of pump laser) both with and without corrections for detector dead time and for stop delay time.

For the sake of exemplification the uncertainty budget, for the lower laser intensity, is reported in table 2.

This result is perfectly compatible with the one obtained with the new scheme, $\eta_1 = 0.448 \pm 0.045$ (or $\eta_1 = 0.486 \pm 0.011$ with least squares fit method). At the moment the uncertainty is larger with the proposed scheme, but a substantial reduction of this can be expected by a further careful metrological analysis and determination of all the corrections and an optimization of the Pockels cell apparatus.

Thus, these first results show that the proposed method could allow an accuracy comparable with the existing ones and, in particular, could be competitive with the one based on measurement of coincidences. It is therefore worth of further accurate metrological studies.
| Quantity | Value | Standard Deviation | Type of Distribution | Sensitivity Coefficient | Uncertainty contribution |
|----------|-------|--------------------|----------------------|--------------------------|--------------------------|
| \( N_i \) | 1832.8 | 9.0 | Gaussian | -0.00026 | 0.00234 |
| \( N_c \) | 874.4 | 5.2 | Gaussian | 0.000546 | 0.00284 |
| \( N_s \) | 131777 | 185 | Gaussian | 5.88 \cdot 10^{-10} | 1.1 \cdot 10^{-7} |
| \( T \) | 9.3 ns | 0.5 ns | Rectangular | 1572 | 7.9 \cdot 10^{-7} |

TABLE II: Uncertainty budget for single-photon detector calibration with traditional PDC scheme (point at lowest pump power). Counts are per second.

VII. CONCLUSIONS

In conclusion we have described the realization of a measurement-conditional unitary gate on biphoton states based on the action of a Pockels cell on a member of a polarization entangled pair of photons conditional to a polarization measurement on the other member. This scheme can find various application to Quantum Information processing and studies of Foundations of Quantum Mechanics.

This unitary gate has then been applied for giving a proof of principle of a new method for absolute calibration of detectors based on rotation of polarization of a member on a PDC biphoton state conditioned to detection of the other member after polarization selection, since the polarization degree of the second state is given by the quantum efficiency of the detector driving the Pockels cell.

These first results show that the proposed method could allow an accuracy comparable with the existing ones and, in particular, could be competitive with the one based on measurement of coincidences. Of course, a further deep investigation of all the details of this scheme and the use of a system realized on purpose will be necessary for really reaching accuracy levels needed for metrological applications.

It must be noticed that in principle this method could be used even if the second detector is an analog one. Furthermore, we are studying the possibility of extending this scheme for calibrating analog detectors as well.

Acknowledgments

We acknowledge support of INTAS, grant #01-2122.

One of us (L.Krivitsky) acknowledges the support of INTAS YS fellowship grant (03-55-1971).

Turin group acknowledges the support of MIUR (FIRB RBAU01L5AZ-002; Cofinanziamento 2001) and Regione Piemonte.

Moscow group acknowledges support of the Russian Foundation for Basic Research, grant #02-02-16664, and the Russian program of scientific school support (#166.2003.02).

[1] see for example M.A. Nielsen and I.L. Chuang, Quantum computation and Information, Cambridge 2000; D. Bouwmeester et al., The physics of quantum information, Springer 2000; N. Gisin et al., [quant-ph 0101098] and ref.s therein.
[2] C.H. Bennett et al., Phys. Rev. Lett. 70, 1895 (1993).
[3] D. Bouwmeester, J. Pan, M. Eibl, H. weinfurter and A. Zeilinger, "Experimental quantum teleportation" , Nature 390, 575 (1997); D. Boschi, S. Branca, F. De Martini, L. Hardy and S. Popescu, "Experimental realization of teleporting an unknown pure quantum state via dual classical and Einstein-Podolsky-Rosen channels", Phys. Rev. Lett. 80 (98) 1121; Y.-H. Kim, S.Kulik and Y. Shih, "Quantum teleportation of a polarization state with a complete Bell state measurement", Phys. Rev. Lett. 86, 1370 (2001).
[4] J.-W. Pan et al., Phys. Rev. Lett. 80, 3891 (1998); T. Jennewein, G. Weihs, J. Pan and A. Zeilinger, "Experimental Nonlocality proof of quantum teleportation and entanglement swapping", Phys. Rev. Lett. 88, 017903 (2002).
[5] S.Giacomini, F. Sciarino, E. Lombardi and F. De Martini, "Active teleportation of a quantum qubit", Phys. Rev. A 66, 030302(R) (2002).
[6] T.B. Pittman, B.C. Jacobs and J.D. Franson, "Single photons on pseudodemand from stored parametric down-conversion", Phys. Rev. A 66 (2002), 042303;
[7] T.B. Pittman, B.C. Jacobs, and J.D. Franson, "Demonstration of feed-forward control for linear optics quantum computation", Phys. Rev. A 66 (2002), 052305.
[8] G. Auletta, Foundations and interpretation of quantum mechanics (World Scientific, Singapore 2000) and ref.s therein.
[9] A. Aspect, J. Dalibard, G. Roger, "Experimental Test of Bell’s Inequalities Using Time- Varying Analyzers", Phys. Rev. Lett. 49 (1982) 1804; J. G. Rarity and P. R. Tapster, "Experimental violation of Bell’s inequality based on phase and momentum", Phys. Rev. Lett. 64 (1990), 2495; P. G. Kwiat et al, "Correlated two-photon interference in a dual-beam Michelson interferometer", Phys.Rev. A. 41 (1990), 2910; W. Tittel, J. Brendel, H. Zbinden, N. Gisin, "Violation of Bell
inequalities by photons more than 10 km apart”, Phys.Rev. Lett. 81 (1998), 3563; E. Kiess, Y. H. Shih, A. V. Sergienko and C. O. Alley, Einstein-Podolsky-Rosen-Bohm Experiment Using Pairs of Light Quanta Produced by Type-II Parametric Down Conversion”, Phys. Rev. Lett. 71 (1993), 3893; P. G. Kwiat, K. Mattle, A. V. Sergienko, Y. H. Shih, H. Weinfurter, A. Zeilinger, ”New high-intensity source of polarization-entangled photon pairs”, Phys. Rev. Lett. 75 (1995), 4337.

[10] See, for example, N. Gisin, G. Ribordy, W. Tittel and H. Zbinden, ”Quantum cryptography”, Rev. Mod. Phys. 74 (2002), 145-195, and refs. therein.

[11] T.B. Pittman, M. J. Fitch, B. C. Jacobs, and J. D. Franson, ”Experimental Controlled-NOT Logic Gate for Single Photons in the Coincidence Basis et al., quant-ph 0303095; T. B. Pittman, B. C. Jacobs, and J. D. Franson, ”Demonstration of nondeterministic quantum logic operations using linear optical elements”, Phys. Rev. Lett. 88 (2002), 257902; E. Knill, R. Laflamme, G. J. Milburn, ”A scheme for efficient quantum computation with linear optics”, Nature 409 (2001), 46.

[12] A. G. White, Daniel F. V. James, Philippe H. Eberhard, and Paul G. Kwiat, ”Nonmaximally Entangled States: Production, Characterization, and Utilization”, Phys. Rev. Lett. 83 (1999), 3103; Y.Kim, S.P.Kulik, Y.Shih, ”Bell State Preparation Using Pulsed Nondegenerate Two-Photon Entanglement”, Phys. Rev. 63 (2001), 060301; Y.H.Kim, M.V.Chekhoua, S.P.Kulik, M.Rubin, and Y.H.Shih, ”Interferometric Bell State Preparation Using Femtosecond Pulse Pumped Spontaneous Parametric Down-Conversion”, Phys. Rev. 63 (2001), 062301; G. Brida, M. Genovese, C. Novero and E. Predazzi, ”New experimental test of Bell Inequalities by the use of a Non-Maximally Entangled photon state”, Phys. Lett. A 268 (2000), 12; G. Brida, M. Genovese, M. Gramegna, C. Novero and E. Predazzi, ”A first test of Wigner function local realistic model”, Phys. Lett. A 299 (2002), 121; M. Fiorentino, G. Messin, C. Kuklewicz, F.N.C. Wong and J.H. Shapiro, ”Generation of ultrabright tunable polarization entanglement without spatial, spectral or temporal constraints”, Phys. Rev. A 69 041801 (R), 2004.

[13] D.C. Burnham and D.L. Weinberg, ”Observation of Simultaneity in Parametric Production of Optical Photon Pairs”, Phys. Rev. Lett. 25 (1970), 84; D.N. Klyshko, Sov. J. Quant. Elect. 10, 1112 (1980); A. A. Malygin, A. N. Penin, A. V. Sergienko, ”Absolute Calibration of the Sensitivity of Photodetectors Using a Two-Photon Field”, Sov. Phys. JETP Lett. 33 (1981) 477.

[14] A. Migdall, ”Correlated-photon metrology without absolute standards”, Physics Today (1999), 41-46, and refs. therein.

[15] G. Brida, M. Genovese and C. Novero, An application of two photons entangled states to quantum metrology”, Jour. Mod. Opt. 47 (2000), 3999, and refs. therein.

[16] G. Brida et al., work in progress, to appear in proc. of CPEM 2004, London.

[17] D.N.Klyshko, JETP 84 (6), 1065 (1997).
When a 90° rotation of polarization is realized by the Pockels cell conditioned to the measurement of a vertically polarized photon on the conjugated branch, the data (triangles) show a clear dependence on the polarizer setting.

When the Pockels cell (KDP) is not activated the maximum is shifted, as expected, by 90° (squares). When a 90° rotation of polarization is realized by the Pockels cell conditioned to the measurement of a 45° polarized photon in the conjugated arm, the maximum is shifted, as expected, to 45° (squares).

When a 90° rotation of polarization is realized by the Pockels cell conditioned to the measurement of a 45° polarized photon in the conjugated arm, the maximum is shifted, as expected, to 45° (triangles).

Fig. 5 Von Neumann entropy of the trigger photon polarization density matrix as a function of the quantum efficiency η1 of the first detector. When η1 = 1 the final polarization reduced density matrix ρ2 of the second photon corresponds to a pure state, giving S(ρ2) = 0. On the other hand if η1 = 0 the final polarization reduced density matrix of the second photon is completely mixed with S(ρ2) = 1.

Fig. 6 Counts on the second detector as a function of the angle of the polarizer preceding it (without background subtraction) in absence of the Pockels cell.

When the Pockels cell (KDP) is not activated a maximum is introduced electronically between the trigger pulses from D1 detector and the corresponding high-voltage pulses driving the Pockels’ cell. The effect of counting rate decreasing for horizontally polarized photons is observed for T < 100 ns and not observed for T > 100 ns.

Fig. 11 Coincidences in function of the counts on the detector under calibration (by varying the power of pump laser) both with (circles) and without (squares) corrections for detector dead time and for stop delay time. These data are used for evaluating the quantum efficiency of the signal detector by means of traditional scheme for biphoton calibration of detectors [13, 14].
Passing of the cw He-Ne laser beam through the crossed polarizers

- • Pulse of the high voltage
- • Intensity of the passed light
