Engineering a C-phase quantum gate: optical design and experimental realization

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Abstract. A two qubit quantum gate, namely the C-phase, has been realized by exploiting the longitudinal momentum (i.e. the optical path) degree of freedom of a single photon. The experimental setup used to engineer this quantum gate represents an advanced version of the high stability closed-loop interferometric setup adopted to generate and characterize 2-photon 4-qubit phased Dicke states. Some experimental results, dealing with the characterization of multipartite entanglement of the phased Dicke states are also discussed in detail.

1 Introduction

Quantum entanglement, defined by E. Schrödinger as “the characteristic trait of quantum mechanics”, represents the key resource for modern quantum information (QI). An entangled state shared by two or more separated parties is an essential resource for fundamental QI protocols, otherwise impossible with classical systems, such as quantum teleportation [1], quantum computing [2], quantum cryptography [3] and quantum dense coding [4]. By using entangled states we can also investigate the nonlocal properties of quantum world [5,6]. Quantum optics represents an excellent experimental test bench for various novel concepts introduced within the framework of QI theory. Quantum states of photons may be easily and accurately manipulated using linear and nonlinear optical devices and measured by efficient single-photon detectors.

Many QI tasks and fundamental tests of quantum mechanics deal with a large number of qubits [7]. For example, the larger the number of qubits, the stronger the violation of Bell inequalities and the computational power of a quantum processor. Two approaches may be followed to increase the number of qubits. By the first one the number of entangled particles is increased [8–11]. In this way, multi-qubit entangled states are created by distributing the qubits between the particles so that each of them carries one qubit. As a second strategy more than one qubit is encoded in each particle, exploiting different degrees of freedom (DOFs) of the photon [12–17]. The entanglement of two photons in different DOFs corresponds to produce a hyperentangled (HE) state. Compared to multiphoton entangled states, HE states offer important advantages as far as purity and generation/detection rate are concerned. The paper is organized as follows: we describe the generation of 4-qubit phased Dicke states based on the hyperentanglement of 2 photons. We will discuss the experimental results concerning the measurement of a novel class of entanglement witness and we will present the first experimental realization of the C-phase quantum gate based only on the path DOF of a single photon.

2 Hyperentanglement source

The SPDC source used in this work [18] is based on the simultaneous entanglement of 2 photons in the polarization-longitudinal momentum DOFs. The scheme of the source is shown in Figure 1. Polarization entanglement is created by double excitation (back and forth, after reflection on a spherical mirror) of a 1 mm Type I BBO crystal by a UV laser beam. The backward emission determines the so called $V$-cone, with SPDC photon polarization transformed from horizontal (H) to vertical (V) by double passage of the two photons through a quarter waveplate (QWP). The forward BBO emission corresponds to the $H$-cone. Temporal and spatial superposition guarantees indistinguishability of the two emission cones and allows for the creation of the polarization entangled state $|H⟩_A|H⟩_B + e^{iγ}|V⟩_A|V⟩_B$, by assuming the following relations between physical and logical qubits: $|H⟩ \rightarrow |0⟩$, $|V⟩ \rightarrow |1⟩$.

The two photons are emitted with equal probability over symmetrical directions on the overlapping cone surface then transformed into a cylinder by the lens L (see Fig. 1). By selecting different pairs of correlated emission modes with single mode fibers [19] or with a 4-hole
screen [20] path- (longitudinal momentum-) entanglement is created. In our experiment, the state \( \frac{1}{\sqrt{2}} (|r\rangle_A|\ell\rangle_B + e^{i\delta}|\ell\rangle_A|r\rangle_B) \) has been generated by selecting 2 pairs of correlated modes. Here \(|r\rangle\) (\(|\ell\rangle\)) stands for the optical path followed by the photons in the right (left) direction, with the following relation between physical states and logical qubits, \(|r\rangle \rightarrow |0\rangle\), \(|\ell\rangle \rightarrow |1\rangle\). The obtained HE state is written as follows:

\[
|HE_\ell\rangle = \frac{1}{2}(|HH\rangle_{AB} + e^{i\gamma}|VV\rangle_{AB}) \otimes (|\ell\rangle_{AB} + e^{i\delta}|r\rangle_{AB})
\]

(1)

The above described scheme has been also used to explore a higher-dimensional Hilbert space [21–23]. In the following we’ll describe the use of this setup to generate and measure phased Dicke states.

3 Hyperentangled phased-dicke states: generation and characterization

In the computational basis \(\{|0\rangle, |1\rangle\}\), the 4-qubit phased Dicke state with 2 excitations (i.e. 2 logic |1\rangle) is defined as follows:

\[
|D^{ph}_{4(2)}\rangle_{1234} = \frac{1}{\sqrt{6}} (|0011\rangle + |1100\rangle + |0110\rangle + |1001\rangle - |0101\rangle - |1010\rangle)_{1234}
\]

(2)

and derives from the 4-qubit symmetric Dicke state \(|D^{(2)}_{4}\rangle_{1234} = Z_1Z_2|D^{ph}_{4}\rangle_{1234} \)

(2)

of generation rate and state fidelity compared to 4-photon states. The measurements were performed by a closed-loop Sagnac scheme with intrinsic almost perfect stability.

3.1 State generation

Here we briefly describe how the experimental setup of Figure 2 has been used in reference [27] to engineer phased
Dicke states. Let us consider the following state $|\xi\rangle_{1234} = \frac{1}{\sqrt{6}}(|0010\rangle - |0100\rangle + 2|0111\rangle)_{1234}$. The phased Dicke state can be obtained by applying a unitary transformation $U$ to the state $|\xi\rangle$:

$$|D_{12}^{(p)}\rangle_{1234} = Z_2 C Z_{12} C Z_{34} C X_{12} C X_{34} H_1 H_3 |\xi\rangle = U |\xi\rangle_{1234}$$

(3)

where $H_j$ and $Z_j$ stands for the Hadamard and the Pauli $\sigma_z$ transformations on qubit $j$, $C X_{ij} = |0\rangle_i |0\rangle_j + |1\rangle_i |1\rangle_j$ is the controlled-NOT gate and $C Z_{ij} = |1\rangle_i |1\rangle_j + |0\rangle_i |0\rangle_j$ the controlled-Z gate (see Fig. 2). The transformations $C Z_{12} C Z_{34}$ are needed to compensate the optical delay introduced by the $C X$ gates in the Sagnac loop of Figure 2b. As explained in the previous section, the $|0\rangle$ and $|1\rangle$ states are encoded into horizontal $|H\rangle$ and vertical $|V\rangle$ polarization or into right $|\ell\rangle$ and left $|r\rangle$ path. The qubit 1 (2) belongs to the path (polarization) DOF of the photon A while the qubit 3 (4) belongs to the path (polarization) DOF of the photon B.

According to those relations the state $|\xi\rangle$ reads:

$$|\xi\rangle_{1234} = \frac{1}{\sqrt{6}}(|r\ell\rangle - |r\ell\rangle)_{13}|H H\rangle_{24} + 2|r\ell\rangle_{13}|V V\rangle_{24}$$

(4)

and may be obtained by suitably modifying the source used to realize polarization-longitudinal momentum hyperentangled states [12,23] (see Sect. 2). Let us consider now the HE state in equation (1) and Figure 2a. The SPDC contribution, due to the pump beam incoming after reflection on mirror $M$, corresponds to the term $|H H\rangle(|r\ell\rangle - |r\ell\rangle)$, whose weight is determined by the quarter waveplate $Q W P_2$ intercepting the UV beam (see [28] for more details on the generation of the non-maximally polarization entangled state). The other SPDC contribution $2|V V\rangle|r\ell\rangle$ is determined by the first excitation of the pump beam: here the $|r\ell\rangle$ modes are intercepted by two beam stops and the quarter waveplate $Q W P_2$ transforms the $|H H\rangle$ SPDC emission into $|V V\rangle$ after reflection on mirror $M$. The relative phase between the $|V V\rangle$ and $|H H\rangle$ is varied by translation of the spherical mirror $M$.

The transformation (3) $|\xi\rangle \rightarrow |D_{12}^{(p)}\rangle$ is realized by using two waveplates and one beam splitter (BS); the two Hadamards $H_1$ and $H_3$ in (3), acting on both path qubits, are implemented by a single BS for both A and B modes. For each controlled-NOT (or controlled-Z) gate appearing in (3) the control and target qubits are respectively represented by path and polarization of a single photon: a half waveplate (HWP) with axis oriented at 45° ($0^\circ$) with respect to the vertical direction and located into the left $|\ell\rangle$ (right $|r\rangle$) mode implements a $C X$ ($C Z$) gate.

After these transformations, the optical modes are spatially matched the second time on the BS, closing in this way a closed-loop Sagnac interferometer that allows high stability in measuring the path Pauli operators (see Fig. 2b). Polarization Pauli operators are measured by standard polarization analysis setup in front of detectors (i.e. PA box in Fig. 2b).

Note that, the $|0\rangle$ ($|1\rangle$) state, for the path DOF, is identified by the clockwise (counterclockwise) mode in the Sagnac loop.

It is worth of stressing once more the high stability guaranteed by the Sagnac interferometric scheme in performing the path analysis.

### 3.2 Entanglement characterization via structural witness

The presence of entanglement in the generated phased Dicke states was tested by adopting a recently proposed class of entanglement witnesses, so-called structural witnesses [29].

For a composite system of $N$ particles, the structural witnesses [29] have the form

$$W(k) := I_N - \Sigma(k)$$

(5)

where $k$ is a real parameter (the three-dimensional wavevector transferred in a scattering scenario), $I_N$ is the identity operator and

$$\Sigma(k^x, k^y, k^z) = \frac{1}{B(N, 2)} \times c_x \tilde{S}^{x<}(k^x) + c_y \tilde{S}^{y<}(k^y) + c_z \tilde{S}^{z<}(k^z),$$

(6)

with $c_i \in \mathbb{R}, |c_i| \leq 1$. Here $B(N, 2)$ is the binomial coefficient and the structure factor operators $\tilde{S}^{\alpha<}(k)$ are defined as

$$\tilde{S}^{\alpha<}(k) := \sum_{i < j} e^{i k(r_i - r_j)} S_i^\alpha S_j^\beta,$$

(7)

where $i, j$ denote the $i$-th and $j$-th spins, $r_i, r_j$ their positions in a one-dimensional scenario, and $S_i^\alpha$ are the spin operators with $\alpha, \beta = x, y, z$. A suitable structural witness $\bar{W}$ for the phased Dicke state can be constructed by considering $k^x = k^y = \pi$ and $k^z = 0$:

$$\bar{W} = I_N - \frac{1}{6} \left[ \tilde{S}^{x<}(\pi) + \tilde{S}^{y<}(\pi) - \tilde{S}^{z<}(0) \right].$$

(8)

The expectation value of the above witness for the phased Dicke state is given by $\text{Tr}(|D_{12}^{(p)}\rangle \langle D_{12}^{(p)}| \bar{W}) = -\frac{1}{2}$, thus leading to a robust entanglement detection in the presence of noise. The witness $\bar{W}$ measured for the phased Dicke state [27], is

$$\langle \bar{W}\rangle_{\text{exp}} = -0.382 \pm 0.012.$$

(9)

We report in Table 1 the experimental values for each operator appearing in the witness (8).

We have also measured a witness $W_{\text{mult}}$, introduced in [30], to demonstrate the genuine multipartite nature of the generated state. This operator is defined as follows:

$$W_{\text{mult}} = 2 \cdot I + \frac{1}{6} (\hat{J}_x^2 + \hat{J}_y^2 + \hat{J}_z^2) + \frac{31}{12} \hat{J}_x^2 - \frac{7}{12} \hat{J}_y^2$$

(10)

where $\hat{J}^2_i = 1 + \frac{1}{2} \tilde{S}^{i<}(k^i)$ and $\hat{J}_i^2 = 1 + \tilde{S}^{i<}(k^i) + \frac{1}{4} (\tilde{S}^{i<})^2(k^i)$, $i = x, y, z$ and $k^x = k^y = \pi$, $k^z = 0$. It comes out that
Table 1. Experimental values of the operators needed to estimate the structural witness in equation (8). The uncertainties are determined by associating Poissonian fluctuations to the coincidence counts. Here $k$ refers to the longitudinal momentum DOF while $\pi$ refers to the polarization DOF.

| Operators | Involved qubits | Local settings | Results |
|-----------|-----------------|----------------|---------|
| $S_{11}^{x}$ | X1X | (X1)(k)(XX)$\pi$ | 0.458 ± 0.013 |
| $S_{22}^{x}$ | 1X1 | (11)(k)(XX)$\pi$ | 0.531 ± 0.012 |
| $S_{33}^{x}$ | 11X | (1X)(k)(11)$\pi$ | 0.384 ± 0.013 |
| $S_{12}^{x}$ | XX1 | (X1)(k)(X1)$\pi$ | 0.545 ± 0.012 |
| $S_{13}^{x}$ | X1X | (XX)(k)(11)$\pi$ | 0.597 ± 0.011 |
| $S_{23}^{x}$ | 1XX | (1X)(k)(11)$\pi$ | 0.620 ± 0.011 |
| $S_{11}^{y}$ | Y1Y | (Y1)(k)(1Y)$\pi$ | 0.617 ± 0.009 |
| $S_{22}^{y}$ | 1Y1 | (11)(k)(YY)$\pi$ | 0.590 ± 0.009 |
| $S_{12}^{y}$ | 11Y | (1Y)(k)(YY)$\pi$ | 0.528 ± 0.009 |
| $S_{13}^{y}$ | Y1Y | (YY)(k)(1Y)$\pi$ | 0.550 ± 0.009 |
| $S_{23}^{y}$ | YYY | (YY)(k)(YY)$\pi$ | 0.523 ± 0.010 |
| $S_{11}^{z}$ | Z1Z | (Z1)(k)(Z1)$\pi$ | 0.327 ± 0.024 |
| $S_{22}^{z}$ | 1Z1 | (Z)(k)(Z1)$\pi$ | 0.304 ± 0.024 |
| $S_{12}^{z}$ | ZZ1 | (Z1)(k)(1Z)$\pi$ | 0.314 ± 0.024 |
| $S_{13}^{z}$ | Z1Z | (ZZ)(k)(11)$\pi$ | 0.308 ± 0.024 |
| $S_{23}^{z}$ | ZZ1 | (ZZ)(k)(11)$\pi$ | 0.315 ± 0.024 |

Table 2. Experimentally measured expectation values of collective spin operators for the phased Dicke state. The uncertainties are determined by associating Poissonian fluctuations to the coincidence counts.

| Operators | Involved qubits | Local settings | Results |
|-----------|-----------------|----------------|---------|
| $1^{\circ}2^{\circ}3^{\circ}4^{\circ}$ | (1$^{\circ}3^{\circ}$)(k$^{\circ}$4$^{\circ}$)$\pi$ | $X_{1}X_{2}X_{3}X_{4}$ | 0.673 ± 0.011 |
| $Y_{1}Y_{2}Y_{3}Y_{4}$ | (YY)(k)(YY)$\pi$ | 0.635 ± 0.009 |
| $Z_{1}Z_{2}Z_{3}Z_{4}$ | (ZZ)(k)(ZZ)$\pi$ | 0.922 ± 0.010 |

this equation, in terms of the operators $\hat{S}^{ii}(k')$ defined in equation (7), reads:

$$W_{mult} = \frac{1}{8} \left( 2 \cdot 1 - 2 \hat{S}^{xx} 2^4(\pi) - 2 \hat{S}^{yy} 2^4(\pi) + \hat{S}^{zz} 2^4(\pi) \right)$$

4 Experimental realization of the C-phase quantum gate

Many efforts have been made in the last years to experimentally implement several basic quantum gates, such as the CNOT or C-phase gate. The latter was in particular realized by exploiting the polarization DOF of a photonic system [31] and, more recently, was implemented within a quantum dot scenario [32]. The unitary transformation corresponding to the C-phase, is defined as follows:

$$U_{phase}^{\pi} = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & e^{i\phi_1} & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & e^{i\phi_2} 
\end{pmatrix}$$

(13)

The optical setup of Figure 3 shows the high stability closed-loop displaced Sagnac scheme used in the experiment. It represents a modified version of the one adopted for the phased Dicke state experiment. Here a second beam splitter (BS2) intercepting only the optical path of lower photon has been added. The particular position of the BS2 enables the realization of a displaced Sagnac interferometer, i.e. an interferometric scheme where the right mode $|r\rangle$ and the left mode $|\ell\rangle$ impinge the BS2 in different points.

Let us now describe how the implemented gate works. In the HE source, described in Section 2, only one polarization cone, namely the $H$-cone, is considered and only one mode, corresponding to the lower photon, is taken into account. In order to explain the experiment let us consider only the $|r\rangle_B$ mode coming out of the hole masked, as reported in Figure 3. The BS1 acts as follows:

$$|r\rangle_B \xrightarrow{BS1} \frac{1}{\sqrt{2}} (|r\rangle_B + |\ell\rangle_B)$$

(14)

The photon, arriving at the BS2, can go clockwise ($|C\rangle_B$) or counterclockwise ($|A\rangle_B$) within the displaced Sagnac. This corresponds to add a further qubit, encoded in the path DOF, hence the state in equation (14) becomes:

$$\frac{1}{\sqrt{2}} (|r\rangle_B + |\ell\rangle_B) \xrightarrow{BS2} \frac{1}{\sqrt{2}} (|r\rangle_B|\phi_1\rangle_B + |\ell\rangle_B|\phi_2\rangle_B)$$

(15)

where $|\phi_1\rangle_B = \frac{1}{\sqrt{2}} (|C\rangle_B + e^{i\phi_1} |A\rangle_B)$, $|\phi_2\rangle_B = \frac{1}{\sqrt{2}} (|C\rangle_B + e^{i\phi_2} |A\rangle_B)$. By considering the following relations between logical states and physical qubits:

$$\{ |0\rangle_1, |1\rangle_1 \} \rightarrow \{ |r\rangle_B, |\ell\rangle_B \}$$
$$\{ |0\rangle_2, |1\rangle_2 \} \rightarrow \{ |C\rangle_B, |A\rangle_B \}$$

(16)

the state (15) reads:

$$\frac{1}{2} [ |0\rangle_1 \otimes (|0\rangle + e^{i\phi_1} |1\rangle_2) + |1\rangle_1 \otimes (|0\rangle + e^{i\phi_1} |1\rangle_2) ] =$$

$$\frac{1}{2} [ (|0\rangle_1 |0\rangle + e^{i\phi_1} |1\rangle_1 |1\rangle_2) + (|1\rangle_1 |0\rangle + e^{i\phi_1} |1\rangle_1 |1\rangle_2) ] =$$

(17)
Fig. 3. (Color online) C-phase gate experimental setup based only on the path DOF of a single photon. The control qubit is identified by the different paths followed by the photon after the BS1 (i.e. |r⟩ or |ℓ⟩), while the target qubit is given by the clockwise (|C⟩) or counterclockwise (|A⟩) path followed by the photon after BS2 within the displaced Sagnac interferometer. The phase shift performed by the gate has been obtained by using the two thin glass plates φr and φℓ, both on the counterclockwise paths |A⟩. Two delays φd allow to compensate the temporal delay introduced by φr and φℓ. The insertion of φ′d is needed to avoid interference between the modes coming back from the displaced Sagnac system and impinging on BS1.

| Logical qubit | Physical qubit |
|---------------|----------------|
| Control | Target | Control | Target |
| | 0⟩ | | | 1⟩ | 0⟩ |
| 0⟩ | 0⟩ | 1⟩ | 0⟩ |
| 1⟩ | 0⟩ | 1⟩ | 0⟩ |

Table 3. “Truth table” of the realized C-phase gate. In the first column we report the logical qubits while in the second column there are the corresponding physical qubits.

The obtained experimental results are shown in Figure 4. We measured the oscillations of the single counts by projecting the state (17) on |0⟩, |0⟩ (|1⟩, |1⟩) and varying φr (φℓ). The projection on |r⟩B⟨r| (|ℓ⟩B⟨ℓ|) was performed by intercepting the input mode |r⟩B ⟨|r⟩B⟩.

In the experiment, φr = φℓ + π, thus there is a particular phase factor between φr and φℓ, however it is important to underline that they can assume any general value with this setup. In the case φr = 0, φℓ = π, we have performed the tomographic reconstruction [33] of the density matrix related to the state |φr⟩B⟨φr| and |φℓ⟩B⟨φℓ|. These values correspond to realize a C − NOT gate. As already pointed out, the second passage through BS2 allows to measure the Pauli operators σx and σy. The third Pauli operator σz has been measured by intercepting the mode in the displaced Sagnac (i.e. |C⟩ or |A⟩). This corresponds to make a projection on the computational basis. The fidelities of the measured states, calculated with respect to the theoretical states, are larger than 98%.
in the previous section. In this case, the modes coming back to the PBS will be sent towards the same detector in the horizontal polarization.

Another possibility, sketched in Figure 5b, concerns the use of path DOF as the control qubit and of polarization DOF as the target. Let us consider the input photon in the state $|\pm\rangle$ encoded in the polarization DOF. Depending on the optical path followed after the BS1, an arbitrary phase can be experimentally assigned to the polarization state by employing liquid crystals [34].

Recent developments of integrated quantum circuits suggest to adopt these systems to realize an intrinsically stable C-phase gate based on path encoded qubits. It has been recently demonstrated that, due to the low birefringence, integrated quantum circuits written by femtosecond laser pulses can support polarization qubits [35–37]. Hence, using this approach to implement the C-phase gate demonstrated in this experiment and the proposed schemes sketched in Figure 5a may open interesting developments in a very challenging research field.

5 Conclusions and discussion

In this work we have presented the main features of a 4-qubit phased Dicke state, built on the polarization and longitudinal momentum of the photons. The entanglement properties have been investigated by a new kind of entanglement witness, so-called structural witness. To generate and measure this state, an interferometric closed-loop Sagnac scheme with almost perfect intrinsic stability has been adopted. An advanced version of this setup has allowed to efficiently implement the C-phase quantum gate based on the optical path of a single photon. We have presented the obtained experimental results and discussed the flexibility showed by the engineered setup.

Other experimental schemes can be conceived to realize such quantum gate. For instance two changes can be implemented (see Fig. 5a):

- by replacing the BS1 with a PBS;
- by exploiting the polarization of the photon after it arrives at the BS1. Precisely it has to be in the state $|\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$ and this can be obtained by placing a half-waveplate rotated by 22.5° with respect to the vertical polarization.

In this case, the PBS will separate the polarization $H$ and $V$ and the displaced Sagnac will act as already explained.

References

1. C.H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, W.K. Wootters, Phys. Rev. Lett. 70, 1895 (1993)
2. R. Raussendorf, H.J. Briegel, Phys. Rev. Lett. 86, 5188 (2001)
3. A.K. Ekert, Phys. Rev. Lett. 67, 661 (1991)
4. C.H. Bennett, S.J. Wiesner, Phys. Rev. Lett. 69, 2881 (1992)
5. A. Einstein, B. Podolsky, N. Rosen, Phys. Rev. 47, 777 (1935)
6. J.S. Bell, Physics 1, 195 (1964)
7. M.A. Nielsen, LL. Chung, Quantum Computation and Quantum Information (Cambridge University Press, 2000)
8. C.A. Sackett, D. Kielpinski, B.E. King, C. Langer, V. Meyer, C.J. Myatt, M. Rowe, Q.A. Turchette, W.M. Itano, D.J. Wineland, C. Monroe, Nature 404, 256 (2000)
9. Z. Zhao, T. Yang, Y.A. Chen, A.N. Zhang, M. Žukowski, J.W. Pan, Phys. Rev. Lett. 91, 180401 (2003)
10. N. Kiesel, C. Schmid, U. Weber, G. Tóth, O. Gühne, R. Ursin, H. Weinfurter, Phys. Rev. Lett. 95, 210502 (2005)
11. C.-Y. Lu, X.-Q. Zhou, O. Gühne, W.-B. Gao, J. Zhang, Z.-S. Yuan, A. Goebel, T. Yang, J.-W. Pan, Nat. Phys. 3, 91 (2007)
12. M. Barbieri, C. Cinelli, P. Mataloni, F. De Martini, Phys. Rev. A 72, 052110 (2005)
13. G. Vallone, E. Pomaro, F. De Martini, P. Mataloni, Phys. Rev. Lett. 100, 160502 (2008)
14. W.B. Gao, C.Y. Lu, X.C. Yao, P. Xu, O. Gühne, A. Goebel, Y.A. Chen, C.Z. Peng, Z.B. Chen, J.W. Pan, Nat. Phys. 6, 331 (2010)
15. J.T. Barreiro, N.K. Langford, N.A. Peters, P.G. Kwiat, Phys. Rev. Lett. 95, 260501 (2005)
16. R. Ceccarelli, G. Vallone, F. De Martini, P. Mataloni, Adv. Sci. Lett. 2, 455 (2009)
17. A. Cabello, A. Rossi, G. Vallone, F. De Martini, P. Mataloni, Phys. Rev. Lett. 102, 040401 (2009)

$^1$ The horizontal polarization is transmitted while the vertical polarization is reflected.
18. C. Cinelli, M. Barbieri, F. De Martini, P. Mataloni, Laser Phys. 15, 124 (2005)
19. A. Rossi, G. Vallone, A. Chiuri, F. De Martini, P. Mataloni, Phys. Rev. Lett. 102, 153902 (2009)
20. C. Cinelli, M. Barbieri, R. Perris, P. Mataloni, F. De Martini, Phys. Rev. Lett. 95, 240405 (2005)
21. G. Vallone, R. Ceccarelli, F. De Martini, P. Mataloni, Phys. Rev. A 79, R030301 (2009)
22. G. Vallone, G. Donati, R. Ceccarelli, P. Mataloni, Phys. Rev. A 81, 052301 (2010)
23. R. Ceccarelli, G. Vallone, F. De Martini, P. Mataloni, A. Cabello, Phys. Rev. Lett. 103, 160401 (2009)
24. R.H. Dicke, Phys. Rev. 93, 99 (1954)
25. N. Kiesel, C. Schmid, G. Tóth, E. Solano, H. Weinfurter, Phys. Rev. Lett. 98, 063604 (2007)
26. R. Prevedel, G. Cronenberg, M.S. Tame, M. Paternostro, P. Walther, M.S. Kim, A. Zeilinger, Phys. Rev. Lett. 103, 020503 (2009)
27. A. Chiuri, G. Vallone, N. Bruno, C. Macchiavello, D. Bruß, P. Mataloni, Phys. Rev. Lett. 105, 250501 (2010)
28. G. Vallone et al., Phys. Rev. A 76, 012319 (2007)
29. P. Krammer et al., Phys. Rev. Lett. 103, 100502 (2009)
30. G. Tóth, W. Wieczorek, R. Krischek, N. Kiesel, P. Michelberger, H. Weinfurter, New J. Phys. 11, 083002 (2009)
31. N. Kiesel, C. Schmid, U. Weber, R. Ursin, H. Weinfurter, Phys. Rev. Lett. 95, 210505 (2005)
32. T. Meunier, V.E. Calado, L.M.K. Vandersypen, Phys. Rev. B 83, R121403 (2011)
33. D.F.V. James, P.G. Kwiat, W.J. Munro, A.G. White, Phys. Rev. A 64, 052312 (2001)
34. A. Chiuri, V. Rosati, G. Vallone, S. Pádua, H. Imai, S. Giacomini, C. Macchiavello, P. Mataloni, Phys. Rev. Lett. 107, 253602 (2011)
35. L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, R. Osellame, Phys. Rev. Lett. 105, 200503 (2010)
36. L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, R. Osellame, Phys. Rev. Lett. 108, 010502 (2012)
37. A. Crespi, R. Ramponi, R. Osellame, L. Sansoni, I. Bongioanni, F. Sciarrino, G. Vallone, P. Mataloni, Nat. Commun. 2, 566 (2011)