Pulsed Energy-Time Entangled Twin-Photon Source for Quantum Communication

J. Brendel, N. Gisin, W. Tittel, and H. Zbinden
Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland
(Received 11 September 1998)

A pulsed source of energy-time entangled photon pairs pumped by a standard laser diode is proposed and demonstrated. The basic states can be distinguished by their time of arrival. This greatly simplifies the realization of 2-photon quantum cryptography, Bell state analyzers, quantum teleportation, dense coding, entanglement swapping, GHZ-states sources, etc. Moreover, the entanglement is well protected during photon propagation in telecom optical fibers, opening the door to few-photon applications of quantum communication over long distances. [S0031-9007(99)08777-3]

PACS numbers: 03.67.Hk, 03.67.Dd, 03.65.Bz

Quantum communication offers fascinating possibilities to physicists: some correspond to potential applications, like quantum cryptography; others explore the quantum world of entanglement, like dense coding, entanglement swapping (entangling particles that never interact), or teleportation (transferring the unknown quantum state from one particle to a distant one) [1–5]. In recent years, quantum communication, like the entire field of quantum information processing, underwent an impressive flow of theoretical ideas. The experiments, however, were generally far behind. This unbalanced situation still remains, except for the 1-qubit quantum cryptography case (actually pseudo-1-qubit, since weak coherent light pulses mimic the qubit) [5]. There is, thus, a clear need for original implementations of the general ideas. In this Letter, we propose a compact, robust (and low cost) source producing energy-time entangled pairs of photons (twin photons) at determined times. The source can be tuned to produce any desired 2-qubit state, in particular, the four Bell states. Contrary to other Bell state sources [6], the basic states of our twin photons are neither based on polarization nor on momentum but on time bins. This allows one to separate the basic states easily, without any optical element, and prevents cross talk during the photon propagation.

We first introduce the basic states of our qubit space. Next, we present our source and an experimental demonstration is discussed. Finally, the potential of our source is illustrated by several examples.

To understand our source, it is useful to start with the simple device of Fig. 1 which can be entirely understood in terms of classical linear optics. First, we analyze it as a preparation device. Let a 1-photon pulse enter the device from the left. Assuming the pulse duration is short compared to the arm length difference long − short of the Mach-Zehnder interferometer, the output consists of two well separated pulses. Let us denote them $|\text{short}\rangle$ and $|\text{long}\rangle$. They form the basis of our qubit space, similar to the usual vertical $|V\rangle$ and horizontal $|H\rangle$ linear polarization states. Hence, the state at the output of our preparation device reads

$$\alpha|\text{short}\rangle + \beta|\text{long}\rangle . \quad (1)$$

The relative norm and phase of the coefficients α and β are determined by the coupling ratio of the beam splitter and the phase shifter, respectively. Hence, any state of the two-dimensional Hilbert space spanned by the basic states $|\text{short}\rangle$ and $|\text{long}\rangle$ can be prepared. The switch of the device recombines the pulses traveling through the short and the long arms without introducing any loss. It could be replaced by a passive (50-50)% beam splitter, at the cost of a 50% loss. Next, the same device can be used as an analyzer. Simply, let the two pulses enter the device from the right. The switch is synchronized such that the pulse corresponding to the ket $|\text{short}\rangle$ takes the long path in the interferometer and vice versa for the other pulse. Hence, at the output (left) of the analyzer, both pulses interfere. Depending on the phase shift and coupling ratio the interference is constructive or destructive and complete or incomplete, respectively, in full analogy with a polarization analyzer.

The correspondence between the polarization states and the states obtained by superposition of the $|\text{short}\rangle$ and $|\text{long}\rangle$ ones can be extended. For example, a polarization beam splitter that separates the basic vertical and

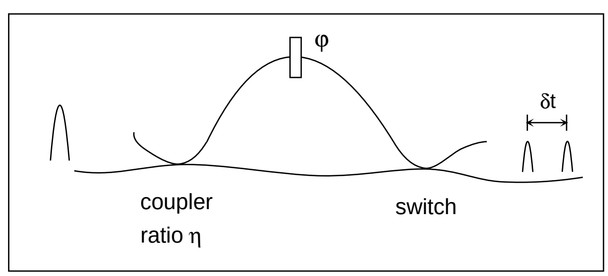

FIG. 1. Schematic of the preparation and analyzer device (using optical fibers and fiber couplers). By adjusting the coupling ratio η of the coupler (beam splitter) and the phase φ of the phase shifter, any superposition (1) of the basic states $|\text{short}\rangle$ and $|\text{long}\rangle$ can be prepared and analyzed ($\frac{|\alpha|^2}{|\beta|^2} = \frac{1-\eta}{\eta}$). The arm length difference δt of this Mach-Zehnder interferometer should be much longer than the pulse duration. The (optional) optical switch allows one to couple or separate the basic states without losses.

 0031-9007/99/82(12)/2594(4)$15.00

horizontal polarization states corresponds to an optical switch between the short and the long pulses.

Our twin-photon source consists of a pulsed pump laser, a device similar to that described above, and a nonlinear crystal where the twin photons are created by spontaneous parametric down-conversion. Each photon from the pump laser is split in two parts by the preparation device, and the two parts pass through the nonlinear crystal with a time delay. Thus, if a pump photon is split into a twin photon, the time of creation of the latter is undefined. More precisely, the preparation device transforms the state of the pump photon in a superposition $\alpha|\text{short}\rangle_{\text{pump}} + \beta|\text{long}\rangle_{\text{pump}}$ and the down-conversion process in the crystal transforms this state into [7]

$$\alpha|\text{short}\rangle_s \otimes |\text{short}\rangle_i + \beta|\text{long}\rangle_s \otimes |\text{long}\rangle_i . \qquad (2)$$

This is similar to the entangled state used for Franson-type tests of Bell inequalities [8]. However, contrary to other sources of energy-time entangled photons [8–11], the coherence of the pump laser of our source is of no importance, as the necessary coherence is built by the preparation interferometer. In other words, the uncertainty of the pump photon's arrival time at the crystal (within the coherence length of the pump laser) is replaced by the two sharp values corresponding to $|\text{short}\rangle$ and $|\text{long}\rangle$ which form the basis of our qubit space. Hence, any standard laser diode, for instance, can be used as the pump.

Figure 2 shows the twin-photon source that we used as a demonstration. It is pumped by a standard red laser diode (Sanyo DL-LS52, $\lambda = 655$ nm) operated in pulsed mode (300 ps pulses, peak power 30 mW, repetition rate 100 MHz). A dispersing prism P deflects any infrared emission of the laser from the entrance of the following bulk optics Michelson interferometer. At the exit of the interferometer the laser pulses are split into two pulses temporarily separated by 1.2 ns. The aperture A guarantees that both pulses belong to the same spatial mode. These

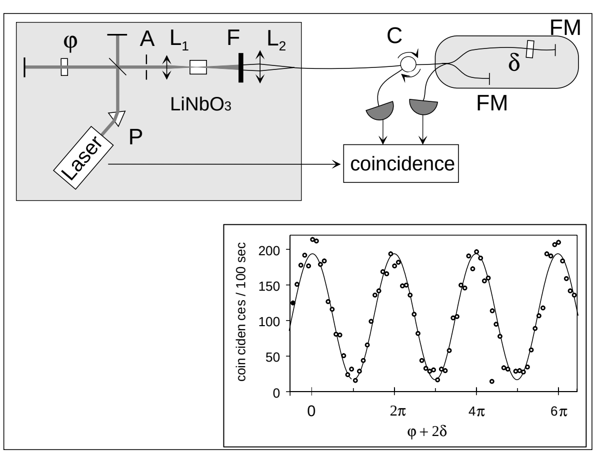

FIG. 2. Schematic of the experiment to demonstrate the twin-photon source. The measured 2-photon interference visibility of 84% establishes the nonclassical nature of the 2-photon field (see inset).

two pulses pass through a nonlinear crystal ($LiNbO_3$) which is cut to produce wavelength degenerated twin photons with a center wavelength of 1310 nm. These twin photons are coupled into a single mode fiber by the coupler L_2, the red laser light being blocked by the filter F. The following analyzer is an all fiber Michelson interferometer with Faraday mirrors (FM) to compensate for polarization fluctuations [10]. The path difference corresponds exactly (within the coherence time of the pump laser) to the delay produced by the first interferometer. It can be varied or maintained stable by controlling the temperature of the whole interferometer. The optical circulator C at the input directs the backreflected photons to one detector; a second is located at the output of the interferometer. Both detectors are passively quenched germanium avalanche photodiodes (APD's) cooled to 77 K. Their quantum efficiency is approximately 6%; the measured single count rates are 41 kHz containing 40 kHz dark counts. We record threefold coincidences between the two detectors and the laser pulser within a 500 ps window.

The inset in Fig. 2 shows the results of a first experiment in which both twin photons are directed to the same analyzer [12]. We characterize our source by measuring the 2-photon interferences produced by the undistinguishable paths: pump photon in the short (long) arm and the two twin photons in the long (short) arm. The observed visibility of 84% clearly exceeds $\frac{1}{\sqrt{2}} \approx 71\%$ which is the upper limit for separable states and, therefore, demonstrates that the twin photons are entangled. The difference to the ideal 100% visibility is attributed mainly to the mismatch between the two interfering modes at the output of the bulk interferometer. We estimate that with an all fiber interferometer, a stronger laser, and by actively biasing the detectors a visibility of more than 95% should be achievable with no more than a few seconds integration time per data point.

Our twin-photon source uses standard components, is compact (in the future it could be fully integrated on an optical chip), and is well adapted for quantum communication over optical fiber networks. Indeed, the separation between the long and short paths can be made large enough to eliminate all drawbacks due to dispersion of the pulses during transmission. Moreover, polarization fluctuations and depolarization, inevitable in optical fibers, have no effect on our system, as already demonstrated by our long distance quantum correlation experiments [10,11]. Another significant advantage of our pulsed source is that the detectors can be opened during only the short time windows when photons are expected. This allows one to gate the detectors and increase the detector efficiency from a few percents to tens of percents. It also opens the door for InGaAs APD which can work at temperatures achievable with thermoelectric cooling but only in such a gated mode [13].

Quantum cryptography could well be the first application of quantum communication. So far all demonstrations outside the lab used the 1-photon scheme [5,14]. Our source should allow a field demonstration of quantum cryptography using the 2-photon scheme [1]. This has the advantage, in addition to elegance, of increasing the distance, since one would start with 1-photon states instead of 0.1 photon weak pulses. Moreover, as illustrated by Fig. 3, our source provides a simple passive detection scheme. For each twin photon, each detector can register a photon at three different times (relative to the emission time): short, medium, long. Short and long counts on Alice's and Bob's sides correspond to the $\{|\text{short}\rangle, |\text{long}\rangle\}$ basis and are 100% correlated. Medium counts correspond to the complementary basis $\{|\text{short}\rangle \pm |\text{long}\rangle\}$ and are also perfectly correlated (assuming $\varphi + \delta_A + \delta_B = 0$). Note that in the first basis, the correlation is in the detection times; whereas, in the second basis the correlation is between the detectors that count the photons. We like to emphasize the relative simplicity of this implementation: usually, in order to avoid an external random number generator and a phase modulator, two analyzers are needed on each side. Here, one of these is realized by simply measuring the time of arrival of the photons; *hence, this analyzer does not require any optical element*.

Other fascinating possibilities of quantum communication are teleportation, entanglement swapping, and dense coding, as already demonstrated in the laboratory [15–18]. Our source provides a means to achieve these tasks over much longer distances. For example, consider the setup of Fig. 4. Two independent—but synchronized—twin-photon sources emit photon pairs. One element of each pair is jointly analyzed by a so-called Bell-state analyzer. Ideally, the eigenstates of this analyzer are the four Bell states:

$$\psi^{\pm} = |\text{short}, \text{long}\rangle \pm |\text{long}, \text{short}\rangle, \tag{3}$$

$$\phi^{\pm} = |\text{short}, \text{short}\rangle \pm |\text{long}, \text{long}\rangle. \tag{4}$$

In practice, however, the best analyzer that can be done using only linear optics separates unambiguously between two of the four Bell states, leaving the two others undistinguished [19]. In our case, such an optimal linear analyzer is straightforward to implement: a 50% beam splitter and two detectors suffice. Indeed, consider first the case of an input state in the space spanned by the $\phi^{\pm}$ states; then both photons arrive simultaneously at one of the detectors (the time of detection of these two photons allows one to distinguish between the $|\text{short}, \text{short}\rangle$ and the $|\text{long}, \text{long}\rangle$ states). Next, if the input state is ψ^-, then necessarily both detectors get one photon but with a time delay. Finally, if the input state is ψ^+, then necessarily both photons propagate to the same detector, again with a time delay. The two $\psi^{\pm}$ states can, thus, be unambiguously distinguished. This happens with a 50% probability, and in these cases the photons of Bob and Charly get entangled, despite the fact that they have never interacted directly. This is called entanglement swapping [3,18]. The same basic configuration could also be used for quantum teleportation [4,16].

A (pulsed) 3-photon source emitting Greenberger-Horne-Zeilinger (GHZ) states [20] (i.e., maximally entangled triplets) could work as follows, generalizing the proposal [21]. Remove one of the detectors of Fig. 4 and consider the cases where the remaining detector registers a photon at the time short. Then, provided there is one photon in each of the three output ports, these three photons are in the GHZ state:

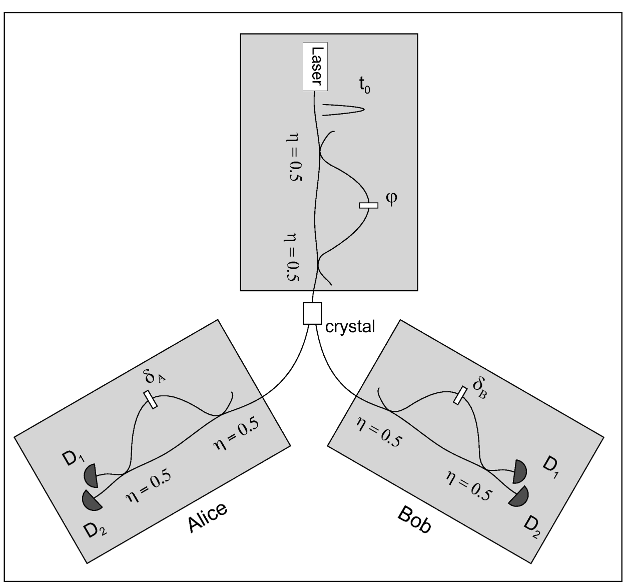

FIG. 3. Implementation of the twin-photon source for quantum cryptography. Alice and Bob require only one interferometer each and no modulators (see text). Note also the analogy between the 3-particle GHZ states and the pump + twin-photon state of this configuration.

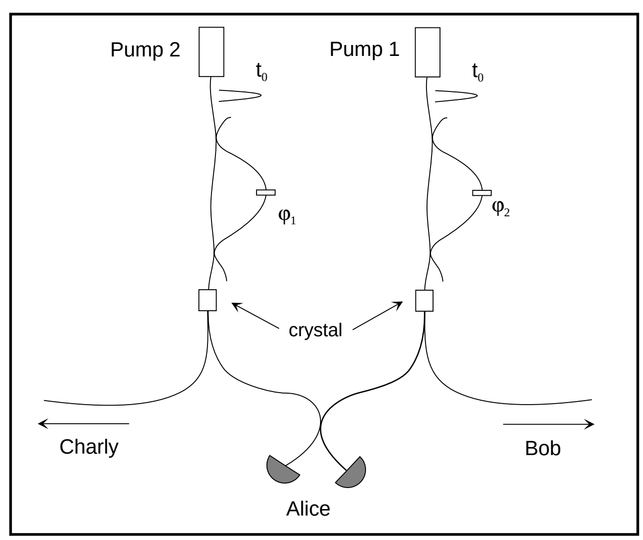

FIG. 4. Application of the two twin-photon source for entanglement swapping and quantum teleportation.

$|\text{short}, \text{long}_1, \text{long}_1\rangle + |\text{long}_2, \text{long}_2, \text{short}\rangle$, where long_j refers to the long arm of the jth source. If long_1 and long_2 are sufficiently different, then this is a GHZ state.

Several generalizations of our proposal are worth mentioning. One could use interferometers with more than two branches, thus providing entanglement of three-dimensional quantum objects (qutrits) or even of higher dimensions [22]. Another generalization would be to prepare the train of coherent pulses that pump the nonlinear crystal from a coherent laser beam and an electro-optical switch. Appropriate electronic driving of such an intensity and phase modulator could allow one to explore entanglement of two objects of dimensions of up to several hundreds (though it is unclear whether all states could be prepared in this way).

In conclusion, a compact and simple twin-photon source has been proposed and demonstrated, and several applications in the field of quantum communication have been described. The use of time as a basis to encode qubits makes it possible to tailor the coherence of the pump beam, starting from any convenient light source. It also allows one to discriminate between the basic states simply by the detection time, thus, simplifying Bell state analyzers. Depolarization during the photon propagation has no effect and polarization fluctuations in the analyzing interferometers can be entirely compensated thanks to Faraday mirrors. All this greatly simplifies the practical implementation of quantum cryptography, teleportation, and other protocols over large distances using telecom optical fibers.

Financial support by the Swiss Priority Programme in Optics is acknowledged.

[1] A. K. Ekert, Phys. Rev. Lett. **67**, 661 (1991).
[2] C. H. Bennett and S. J. Wiesner, Phys. Rev. Lett. **69**, 2881 (1992).
[3] M. Żukowski, A. Zeilinger, M. A. Horne, and A. Ekert, Phys. Rev. Lett. **71**, 4287 (1993).
[4] Ch. Bennett *et al.,* Phys. Rev. Lett. **70**, 1895 (1993).
[5] See, for example, Phys. World **11**, No. 3 (1998).
[6] See, in particular, P. G. Kwiat, H. Weinfurter, A. Zeilinger, and Y. H. Shih, Phys. Rev. Lett. **75**, 4337 (1995); P. G. Kwiat and A. G. White, in *Proceedings of the International Quantum Electronics Conference, 1998* (OSA, Washington, DC, 1998), p. 144.
[7] Actually, the pump pulse consists of many photons in a coherent state. For a count rate of 1 MHz and coincidence window of 1 ns, the probability of two pairs is about 10^{-3} below the probability of a single pair. Hence, we effectively postselect one of the pump photons.
[8] J. D. Franson, Phys. Rev. Lett. **62**, 2205 (1989).
[9] J. Brendel, E. Mohler, and W. Martienssen, Europhys. Lett. **20**, 575 (1992); P. G. Kwiat *et al.,* Phys. Rev. A **47**, R2472 (1993); P. R. Tapster, J. G. Rarity, and P. C. M. Owens, Phys. Rev. Lett. **73**, 1923 (1994).
[10] W. Tittel *et al.,* Phys. Rev. Lett. **81**, 3563 (1998).
[11] W. Tittel *et al.,* Phys. Rev. A **57**, 3229 (1998).
[12] J. Brendel *et al.,* Phys. Rev. Lett., **66**, 1142 (1991).
[13] G. Ribordy *et al.,* Appl. Opt. **37**, 2272 (1998).
[14] C. Marand and P. Townsend, Opt. Lett. **20**, 1695 (1995); R. Hughes *et al.,* Lect. Notes Comput. Sci. **1109**, 329 (1996); H. Zbinden *et al.,* Electron. Lett. **33**, 586 (1997).
[15] K. Mattle, H. Weinfurter, P. G. Kwiat, and A. Zeilinger, Phys. Rev. Lett. **76**, 4656 (1996).
[16] D. Bouwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, Nature (London) **390**, 575 (1997).
[17] D. Boschi, S. Branca, F. De Martini, L. Hardy, and S. Popescu, Phys. Rev. Lett. **80**, 1121 (1998).
[18] J. W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **80**, 3891 (1998).
[19] H. Weinfurter, Europhys. Lett. **25**, 559 (1994).
[20] D. M. Greenberger, M. A. Horne, A. Shimony, and A. Zeilinger, Am. J. Phys. **58**, 1131 (1990).
[21] A. Zeilinger, A. A. Horne, H. Weinfurter, and M. Żukowski, Phys. Rev. Lett. **78**, 3031 (1997).
[22] M. Żukowski, A. Zeilinger, and M. A. Horne, Phys. Rev. A **55**, 2564 (1997).