PHYSICAL REVIEW A, VOLUME 62, 032311

Nondestructive single-photon trigger

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(Received 16 March 2000; published 17 August 2000)

A triggering device sensitive to a single photon is discussed. It is based on a balanced quantum nondemolition (QND) measurement proposed by Chuang and Yamamoto [Phys. Rev. Lett. **76**, 4281 (1996)]. The balanced measurement measures the total photon number and obtains no which-path/mode information. Hence, the timing of the photon can be determined without destroying its wave function or entangling the probe field. This could have extensive use in the realization of long-distance quantum communications systems.

PACS number(s): 03.67.Hk, 03.65.Bz, 42.25.Hz

I. INTRODUCTION

Nondestructive, single-photon-sensitive triggers can play key roles in several quantum optics applications. For example, there is significant interest in teleporting a quantum state to arbitrarily large distances. However, the experimental realization of teleportation has been confined to the laboratory [1,2]. Part of the difficulty of extending the teleportation device to large distances is timing the introduction of a third photon so that it can undergo a Bell measurement with one of the photons in an Einstein-Podolsky-Rosen (EPR) entangled pair. A Bell measurement requires indistinguishability between the third photon and the photon from the EPR pair. If the photons are not time synchronized correctly, then the photons are distinguishable and the teleportation will not occur. Likewise, similar timing requirements are present with entanglement swapping [3]. A single-photon trigger in an entanglement swapping scheme will be presented later on in this paper. A translucent eavesdropping device also requires a single-photon trigger [4]. Suppose Eve wishes to entangle a photon to the communication photon being sent to Bob from Alice. This type of translucent attack would require a knowledge of the position of the communication photon. Without a knowledge of the position of the communication photon, Eve does not know when to introduce her entangling photon. The strength of entanglement is very much a function of the interaction of the photons in a given time interval.

II. BALANCED QND MEASUREMENT

The single-photon trigger is based upon a balanced quantum nondemolition measurement. Chuang and Yamamoto showed that a balanced quantum nondemolition (QND) measurement will measure the existence of a photon without destroying its wave function [5]. Chuang and Yamamoto employed the balanced QND measurement as an important tool in quantum bit regeneration. The idea presented in this report expands on their work. The trigger proposed here not only measures the existence of the photon but determines the position of the photon without destroying any of the quantum information or entangling the probe field.

A balanced QND measurement is one in which a QND measurement of equal strength is taken on all possible spatial or polarization modes of the photon. The standard interaction Hamiltonian [6,7] for a QND measurement is given by

$$\hat{H}=2\hbar\chi\hat{n}_m\hat{n}_M \tag{1}$$

where the subscripts of the number operators denote the field mode. For example, $\hat{n}_m$ denotes that it is operating on field mode *m*. We assume no self-phase modulation. Also, χ is a function of frequency and intensity and can be adjusted. The number operator is a constant of the motion. By complementarity the phase of the photons will be changed. The QND operation in the Fock state basis is then given by

$$\hat{q}=e^{i\delta\hat{n}_m\hat{n}_M} \tag{2}$$

where δ is the net cross-phase shift [6].

III. SINGLE-PHOTON TRIGGER

Consider the single-photon trigger example shown in Fig. 1. In this figure the trigger is used in a long-distance entanglement swapping experiment similar to the one presented in [3]. In this entanglement swapping scheme, the EPR source 1 emits a polarization entangled pair of photons. The photon traveling to the left is coupled into a polarization maintaining fiber and propagates a significant distance. As the photon approaches the second source it must pass through the trigger. The trigger measures the arrival time of the photon (up to the sampling rate of the trigger) and triggers the EPR source 2 to emit a polarization entangled pair of photons. The right photon of the EPR pair 2 will enter one of the input ports of the 2×2 fiber coupler (FC) at the same time (up to the coherence time of the single photons) as the left photon of the EPR pair 1 enters the other port of the fiber coupler. Narrow bandwidth filters (narrower than the bandwidth of the photons from the EPR pairs) will increase the coherence length of the photons and erase any which-path information [3]. If all which-path information is erased, a Bell measurement will occur and entangle the two remaining photons from the crystals [3].

The trigger is outlined in a dashed box in Fig. 1. The trigger measures the photon amplitudes in two orthogonal polarization modes. We assume that the single photons are in a linear polarization basis having horizontal and vertical eigenstates. A QND measurement is taken on the vertical mode of the photon labeled VQND followed by a QND mea-

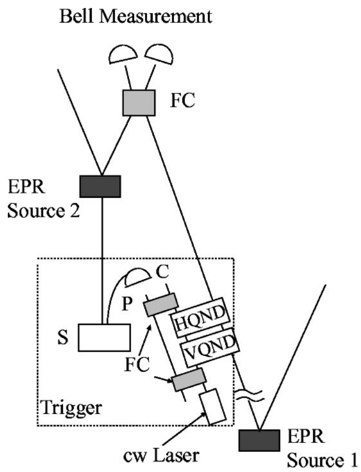

FIG. 1. Entanglement swapping device employing a nondestructive single-photon trigger. An EPR source generates a polarization entangled pair of photons. A trigger measures the vertical and horizontal amplitudes of the photon using two consecutive QND measurements labeled VQND and HQND, respectively. A probe field in a Mach-Zehnder interferometer gets a net phase shift from the QND measurements. Without a single-photon from the EPR source 1, all of the light in the probe field exits port *C*. When a single-photon passes through the trigger, part of the probe field exits port *P*. That light is detected and in turn triggers the EPR source 2. If calibrated two photons, one from each EPR source, will enter the 2×2 fiber coupler and will undergo a Bell measurement and ''swap entanglements'' with the remaining, unmeasured two photons.

surement on the horizontal mode of the photon labeled HQND. As a note, appreciable single-photon polarization-dependent QND measurements have been proposed [8] and realized [9]. The strength of the HQND and VQND interactions must be equal to achieve the trigger that is desired.

The QND measurements create a cross-phase modulation on a probe field $|\Phi\rangle$ in the arm of a Mach-Zehnder interferometer. The Mach-Zehnder interferometer consists of two lossless symmetric 2×2 fiber couplers [10]. The Mach-Zehnder interferometer is calibrated such that when a single photon is not present in the entanglement swapping device all of the light exits the port labeled *C*. When a single photon is present some of the intensity of probe field exits port *P*. The intensity is detected and the synchronization source *S* causes the EPR source 2 to emit a pulse of light to generate an entangled pair.

We now demonstrate that the trigger does not affect the single-photon wave function or entangle the probe field. The wave function of the single photon can be written in terms of Fock states

$$\alpha|0\rangle_h|1\rangle_v+\beta|1\rangle_h|0\rangle_v, \tag{3}$$

where the h and v denote the polarization mode of the single photon. Also, $\alpha^2+\beta^2=1$. Considering only the portion of the probe field $|\Phi\rangle$ that is in the cross-phase modulated arm of the Mach-Zehnder interferometer, then before measurement the wave function of the system can be written as

$$|\Psi_0\rangle=(\alpha|0\rangle_h|1\rangle_v+\beta|1\rangle_h|0\rangle_v)|\Phi\rangle. \tag{4}$$

The first QND measurement acting on the h polarization mode and the probe field yields

$$|\Psi_1\rangle=\alpha|0\rangle_h|1\rangle_v|\Phi\rangle+e^{i\delta\hat{n}_M}\beta|1\rangle_h|0\rangle_v|\Phi\rangle, \tag{5}$$

where the $\hat{n}_M$ operates only on the probe field. After the first QND measurement the probe field is entangled to the single-photon field. The second QND measurement acting on the v polarization mode and the probe field yields

$$|\Psi_2\rangle=e^{i\delta\hat{n}_M}\alpha|0\rangle_h|1\rangle_v|\Phi\rangle+e^{i\delta\hat{n}_M}\beta|1\rangle_h|0\rangle_v|\Phi\rangle. \tag{6}$$

This can be rewritten

$$|\Psi_2\rangle=(\alpha|0\rangle_h|1\rangle_v+\beta|1\rangle_h|0\rangle_v)e^{i\delta\hat{n}_M}|\Phi\rangle. \tag{7}$$

After the second QND measurement the probe field is no longer entangled to the single-photon field, since its quantum state can be factored from the single-photon field. In addition, the wave function of the single photon remains unchanged.

The point we wish to emphasize is that the existence of the single photon caused a phase shift on the probe field without changing the single-photon wave function. The net phase shift between the existence and nonexistence of a communication photon is recorded as intensity fluctuations in detector *P*, which acts as a trigger for the production of another EPR pair of photons.

IV. DISCUSSION

There are a few points to consider with the trigger. While the probe field is continuous, the measuring device must have a sampling rate approximately the same period as the coherence length of the single photon. If the sampling rate is higher, then according to Heisenberg's uncertainty principle the bandwidth of the photon will be increased proportionally. If the sampling rate is lower, the position of the photon will not be known well enough to perform the appropriate operation. Hence, the single-photon wave packet position is only known up to the sampling rate of the probe field. This implies that there is an uncertainty in initializing the creation of another EPR pair. In order to erase any which-path information, it would be necessary to extend the coherence length of the photons in the Bell measurement by using narrow bandwidth filters [3].

Also of great importance is the realization that it is not necessary to have a QND measurement which generates a π cross-phase modulation. Any cross-phase modulation which yields a relatively good signal to noise ratio in the trigger is sufficient for a trigger. In other words as long as the noise fluctuations of intensity in port *P* are small compared to the intensity out of port *P* when a single photon is present, the trigger will work well. The triggering device could be built with current quantum nondemolition technology [8,9,11,12].

One of the most difficult challenges lies in the fact that the QND cross-phase modulations are very sensitive to frequency. For example in [9], it is conceivable that single photons could be detected having a bandwidth not much larger than a few hundred MHz. Hence, large fluctuations in frequency can make single-photon detection very difficult. Spontaneous parametric down-converted (SPDC) photons have large bandwidths [13,14]. This would imply that a trigger and quantum bit regeneration [5] would be difficult to implement using SPDC photons. On the other hand, a source that achieved entanglement using QND measurements would already satisfy the narrow frequency demands [15]. Frequency standards might also be improved with entanglement sources based on the Coulomb blockade in quantum dots [16].

Consider the following numerical example. Suppose a source is emitting entangled photons having bandwidths of 200 MHz. Then $\Delta\nu\Delta t\approx 1$, which implies $\Delta t\approx 5$ ns. This means, using the techniques described above, the position of the photon is known to within 5 ns. If we sample faster than 200 Mhz, then the uncertainty in position goes down, but the bandwidth goes up complementary. Hence, the sampling period should be set at approximately the uncertainty in time. However, this also means that the second source will have a 5 ns window of time in which to create an entangled pair. The two photons going into the Bell measurement would then be distinguishable, because we would know when the second source triggered, and its coherence length. To prevent indistinguishability, it is necessary to place filters that are narrower than 200 MHz in front of the Bell detectors. In [3] the source photons had temporal creation windows of 200 fs and the filters effectively lengthened the coherence length to 500 fs, causing indistinguishability of the photons at the beam splitter. For this scheme, using an equivalent factor of 2.5 for the filters and initial coherence length, it would then require filters having bandwidths less than 80 MHz to achieve similar fringe visibilities. As a note, this triggering device could also be used as a high quantum efficiency narrow filter detector, where the filter bandwidth was determined by the system used.

Practical long-distance communications primarily employ the use of fiber networks [17]. Hence, fiber couplers, instead of beam splitters, and polarization maintaining fiber, instead of free space, were used. This also means that fiber to free space to fiber collimating optics are required to implement the QND measurements of the trigger.

We have described and analyzed a nondestructive trigger sensitive to a single photon. The trigger measures the position/timing of a single-photon in order to time-synchronize any instruments. The measurement does not alter the single-photon wave function or entangle the probe field. The hope is that the trigger will be useful in making large-distance optical communications (e.g., quantum teleportation, entanglement swapping, etc.) a reality.

Note added in proof After resubmission of this paper, we learned of work on narrow-band spontaneous parametric down-converted sources.

ACKNOWLEDGMENT

This work was supported by the National Science Foundation under Grant No. PHY-9733643.

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