A SINGLE-PHOTON ON-DEMAND SOURCE WITH DECOUPLED SINGLE AND MULTIPHOTON PROBABILITIES: INITIAL RESULTS

A. MIGDALL, D. BRANNING,* S. CASTELLETTO,† AND M. WARE

Optical Technology Division, National Institute of Standards and Technology, 20899-8441 Gaithersburg, Maryland (USA)

We present an analysis of a multiplexed downconversion system designed to produce a single-photon on-demand source, by a multiple delay line trigger, yielding a single-photon certification of the produced photons. We discuss theoretically a simple implementation of the system together with initial experimental results.

The advent of photon-based quantum cryptography, communication and computation schemes[1–4] is increasing the need for light sources that produce individual photons; as unwanted additional photons can render quantum cryptographic links insecure and degrade quantum-computation efficiencies.[5] More specifically, it would be useful to have these photons created in response to an external trigger, or even to have them arrive repetitively at a fixed, but selectable rate. As currently implemented, single-photon sources cannot be made to produce single photons with high probability, while simultaneously suppressing the probability of yielding two or more photons. Because of this fact, single photon sources cannot really produce single photons on demand. We have previously described a multiplexed parametric downconversion (PDC) system that allows the probabilities of producing one and more photons to be adjusted independently, enabling a better approximation of a source of single photons on demand.[6] Also described was a simplified version of that scheme that retains significant advantages, while greatly easing its implementation (Fig. 1). That implementation allows photons to be produced along with a quantitative "certification" that they are single photons. Some of the single-photon certifications can be significantly better than what is possible with conventional downconversion sources using a unified trigger detector region or with faint laser sources. We present a comparison of the relative merits of these methods along with the first experimental results obtained with a 4-delay-line setup.

Single-photon production schemes, whether based on faint lasers or PDC, suffer from the problem that the rate of producing unwanted multiple photons is tied to the single-photon rate. The two-photon rate grows as the single-photon rate squared. To reduce the multiphoton rate, the single photon rate must be kept small. Moreover it requires operation in a regime where it is mostly likely that no photons are produced at all! Of course, PDC schemes

---

*CURRENTLY AT UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
†ALSO AT ISTITUTO ELECTROTECNICO NAZIONALE G. FERRARIS (ITALY)

have an advantage over faint laser sources in that the existence of a twin or "herald" photon allows the discrimination against the case where no photon is produced.[a]

By adjusting light levels, for a faint laser source (described by Poisson statistics), the maximum fraction of pulses containing just a single photon is 37%. For a conventional PDC source, that is described by thermal statistics (for a single mode of the field), the maximum possible fraction of single-photon pulses is only 25%.[b] Fortunately, the existance of a herald photon in the PDC case provides for the elimination of the cases where no photon is produced. Eliminating those cases allows the single photon fraction of a PDC source to be improved to 50%.

The multiplexed PDC schemes[6] allow these single-photon fractions to be improved upon by extracting more information out of the herald photon. The simplest of these schemes is shown in Fig. 1. A type I PDC source is shown producing photon pairs with azimuthal symmetry around the pump beam direction. A series of fibers of increasing lengths is arranged azimuthally, but compactly to collect trigger or "herald" photons, while a single lens collects the photons correlated to those collected by the trigger fibers. While the deadtime of the detector is such that it prevents more than one photon from being detected from a pump pulse (also the detector has no multiphoton detection capability), the time of detection relative to the pump pulse tells which delay path the photon took to cause the detector firing. This piece of information (along with the detector efficiency) allows us to determine the likelihood or "certification" that the signal channel contains just a single photon. The results of an analysis of this system is as follows.[6] The probability, in the simple scheme, that only one photon was incident into the entire system of delay paths given that the ith delay path caused the firing is

$$P_{\overline{n},\eta,N_{\text{D}}}(i) = \left(\frac{N_{\text{D}}}{\overline{n} + N_{\text{D}}}\right)^{i-1+N_{\text{D}}} \times \left(\frac{N_{\text{D}} + \eta\overline{n}}{\overline{n} + N_{\text{D}}}\right)^{i}, \qquad (1)$$

where η is the probability of the detector firing when just one photon is incident, $\overline{n}$ is the mean photon number per pulse, and N_{D} is the number of delay lines. The probability in the simple scheme of producing just a single photon given that the trigger detector did fire is

$$P_{\overline{n}}(1, \eta, N_{\text{D}}|trigger) = \frac{\overline{n}\eta \left(\frac{N_{\text{D}}}{\overline{n} + N_{\text{D}}}\right)^{1+N_{\text{D}}}}{1 - \left(\frac{N_{\text{D}}}{\overline{n}\eta + N_{\text{D}}}\right)^{N_{\text{D}}}}. \qquad (2)$$

Fig. 2 shows a summary of the overall probabilities of single-photon emission

---

[a]For PDC and laser sources the photon production time is restricted to a narrow window.
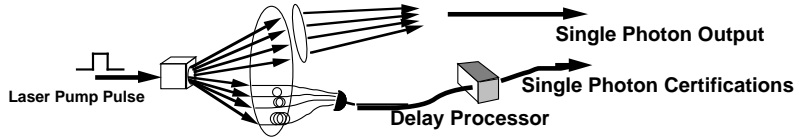[b]For both of these cases this maximum is achieved at a mean photon number per pulse of 1.

2

Figure 1. Single crystal and single detector implementation of scheme. Sequential series of delay lines is seen leading to the trigger detector. A lens collects all the modes correlated to those seen by the trigger.
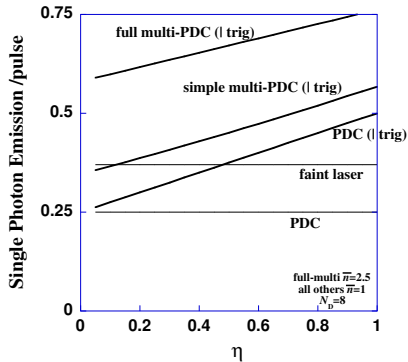

Figure 2. Single photon emission fraction (per pulse). For the full multiplexed PDC $\bar{n}$=2.5, for all other curves $\bar{n}$=1. A system of N_D=8 was used for the multiplexed calculation.

for different sources as a function of detector efficiency. The maximum single-photon fraction (per pulse) for a faint-laser system and a conventional PDC source is given by the two horizontal lines, as they are independent of η. The maximum fraction of a single-channel PDC source taking advantage of the herald is shown rising to the 50% level at η=1. The fraction achievable by the simplified PDC scheme described above is shown surpassing the faint laser fraction at $\eta \approx 0.1$ and rising to 57% at η=1. For completeness, we provide the single-photon fraction for the full multiplexed PDC system described in ref.[6] (This last scheme allows one to take advantage of higher $\bar{n}$'s than is possible with the single-channel systems.)

We implemented the simple multi-PDC scheme of Fig. 2 with 4 fiber-optic delay lines bundled and imaged onto a single-photon counting module detector with a 200 μm diameter active area. The pump is an 82 MHz mode-locked Argon ion laser operating at 458 nm, with a pulse width of 200 ps. The PDC crystal is KDP cut for an emission angle of approximately 1.5 deg at the degenerate wavelength. Four lenses couple single modes of downconverted photons to each single-mode fiber.

We have successfully aligned 4 delay lines and observed a well-resolved multicoincidence peak (Fig. 3) with a spacing of 2.42 ns (the difference be-
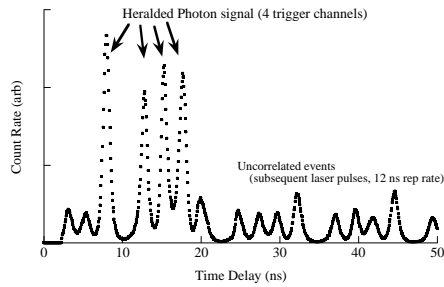
3

Figure 3. Time correlations between 4-channel trigger and single signal channels.

tween delay line lengths). The 4.95 ns gap between the first and second peak is because we skipped an intermediate fiber length in our trigger fiber bundle. A raster scan of the signal detector verified that all 4 correlated beams were superimposed at the detector and thus could be collected simultaneously. Careful adjustment of the lens-detector distance is required to make this happen.

We have shown initial results of a single-photon source scheme that has advantages over conventional single-channel single-photon sources. The system when fully implemented will provide single photons with individualized single certifications. This is the first step in a program to construct a better approximation of a true single-photon on-demand source than is possible using a conventional single PDC setup or a faint-laser source.

References

1. C. Bennett and G. Brassard, *Proceedings of the IEEE International Conference on Computers, Systems and Signal Processing*, 175 (1984).
2. A. Ekert, *Phys. Rev. Lett.* **67**, 661 (1991).
3. C. H. Bennett, G. Brassard, and N. D. Mermin, *Physical Review Letters* **68**(5), 557 (1992).
4. W. Tittel, J. Brendel, H. Zbinden, and N. Gisin, *Physical Review Letters* **84**(20), 4737 (2000).
5. G. Brassard, N. Lutkenhaus, T. Mor, and B. C. Sanders, *Physical Review Letters* **85**(6), 1330 (2000).
6. A. Migdall, D. Branning, S. Castelletto, and M. Ware, quant-ph/0209103, in press SPIE Vol 4821., A. Migdall, D. Branning, S. Castelletto, and M. Ware, in press *Physical Review A*.

4