

## Tailoring single-photon and multiphoton probabilities of a single-photon on-demand source

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As typically 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, single-photon sources cannot really produce single photons on demand. We describe a multiplexed system that allows the probabilities of producing one and more photons to be adjusted independently, enabling a much better approximation of a source of single photons on demand.

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The advent of photon-based quantum cryptography, communication, and computation schemes [1,2] is increasing the need for light sources that produce individual photons. It is of particular importance that these single photons be produced in as controlled a manner as possible, as unwanted additional photons can render quantum cryptographic links insecure and degrade quantum computation efficiencies [3].

Single photons are now commonly created via the process of parametric down-conversion (PDC) [2,4,5], although attenuated lasers and quantum dots and other single-quantum-site sources are also used [6–9]. Because PDC creates photons in pairs, the detection of one photon indicates, or “heralds,” the existence of its twin, a significant advantage over other methods (even aside from the potential to directly produce entangled states). In addition, because the PDC process is governed by the constraints of phase matching, it is possible to know the output trajectory, polarization, and wavelength of that heralded photon. While PDC has a long history as a single-photon source and there have been many recent improvements [10], the scheme has a couple of problems. The conversion process is random, so while an output photon is heralded by its twin, there is no control or prior knowledge of when the heralding event will occur. In addition, there is a possibility of producing more than one pair at a time and because that probability increases nonlinearly with the one-photon probability, one must operate at low one-photon probabilities. So to be assured that more than one photon is not produced, one must operate where it is most likely that no photon is produced at all [11].

The faint laser scheme suffers the same difficulty as the PDC method, in possibly producing more than one photon at a time, with the added difficulty of not having any herald at all [12]. Quantum-dot sources offer a new way of definitively producing single photons, although it remains to be seen whether their output efficiencies can be made to approach unity in practice, a requirement for a true on-demand source.

To surmount the problem of random production in PDC, one uses a pulsed laser to pump the nonlinear crystal (see, for

instance, Ref. [8]). With a pulsed source, photon pairs can only be produced at certain times. Unfortunately the multiple-photon emission problem remains; a high probability,  $P_1$ , of producing a single-photon pair during each pulse leads to an increased likelihood,  $P_{>1}$ , of producing more than one photon pair during each pulse, defeating the original goal of having a source of single photons. This problem occurs regardless of whether sources with Poisson or Bose statistics are used [5,14]. Because of this, pulsed systems are usually operated with low probability of producing an output photon pair during a laser pulse ( $P_1 \approx 0.1-0.3$ ) [6,8,12]. Thus, while photons can only come during specific time windows, most of these time windows will contain no photons at all, showing the trade-off between the two requirements of producing a photon on demand and being assured that there is, in fact, just one photon.

The improvement presented here allows these two competing requirements to be adjusted independently by decoupling  $P_1$  and  $P_{>1}$ . We can then select both the desired likelihood of production of a photon pair and the desired suppression of multiple-pair events. This is accomplished using an array of down-converters and detectors [Fig. 1(a)]

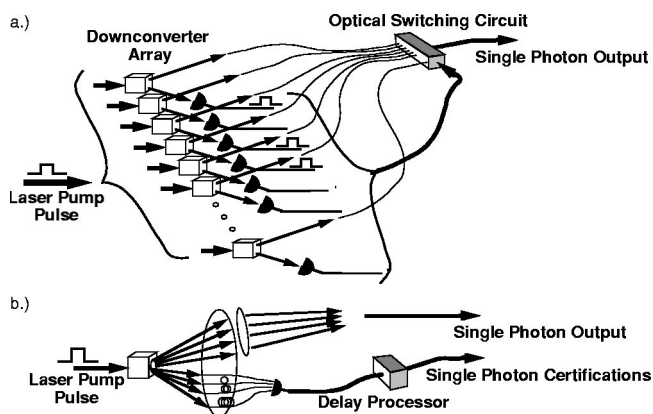


FIG. 1. (a) Single-photon source using an array of crystals and trigger detectors. Which-trigger information is sent to the optical switching circuit. Input line delays to allow the trigger information to arrive before the incoming photons are not shown. (b) Simplified implementation using only a single down-converter crystal and detector and no optical switching circuit. Multiple staggered length delays are shown leading to the trigger detector. A lens collects all the modes correlated to the trigger.

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pumped simultaneously by the same laser pulse. The laser power is chosen so that each down-converter has some small probability of producing a photon pair, while the number of down-converters is chosen so that there is a high likelihood of at least one pair being created somewhere in the array. The detector associated with each down-converter allows us to determine which of the down-converters has fired. This information is used to control an optical switching circuit directing the other photon of the pair onto the single-output channel. This arrangement allows a much truer approximation of a single-photon on-demand source than with other methods.

A simple extension of this arrangement can produce a regularly spaced series of single photons. By ganging up a series of these *single-photon on-demand setups* with additional optical switches and a series of optical delays, it is possible to produce an arbitrary length train of single photons. By producing a pulse train long enough to last until the next pump-laser pulse arrives, one can create a continuous train of single-photon pulses synchronized with an external signal.

These basic concepts could be used to produce higher-order photon number states as well. By using detectors with the capability of sensing the number of photons in a single pulse, the switching circuit could just as well direct the outputs of those converters that produced multiple-photon pairs to the output channel. That would result in an output pulse train with each pulse containing the desired number of photons.

While the scheme just described is conceptually the simplest way of presenting the method, there are a number of modifications that can improve the efficiency, construction, and convenience of the system. The first of these is that the array of down-converters can be implemented with a single PDC crystal. This is possible because while phase matching requires a PDC photon pair to be constrained to a plane containing the pump beam, the azimuthal angle is not constrained. Thus, the PDC process produces light distributed azimuthally around the pump laser direction (for type I phase matching). So, each azimuthal plane can be thought of as a separate down-converter. Thus the multiple PDC setup is achieved by placing many detectors azimuthally in an annular pattern around the pump direction of a single down-converter and collecting at the correlated positions.

A second modification allows the array of detectors to be replaced by a single detector. By sending each of the potential herald photons to an increasing sequence of delays and then directing the delay outputs to a single detector, the timing of the detector pulse indicates which of the input down-converters has created a pair. Of course, several of the down-converters may produce a photon pair, but only one photon herald received by the detector causes it to fire. Detector deadtime causes subsequent photons to be ignored. The timing of the detector pulse is used to select which correlated photon channel to direct to the output of the system.

A third implementation [Fig. 1(b)] even eliminates the output switching network circuit, while still maintaining a significant advantage over both the conventional PDC and faint laser photon sources. The output photons are simply

collected with a single lens output port. This most basic implementation allows production of pulses with individual certainties of that pulse containing exactly one photon. In other words, this source provides single photons and a “certificate” tied to each output photon quantifying the likelihood that just one photon was emitted. Some of these pulses can achieve a significantly higher single-photon certainty than is possible with the conventional single-photon source setups. This more complete characterization of the emitted pulse and its tighter constraints on  $P_{>1}$ , will allow more efficient use of the emitted light. This reduces the need for overhead tasks such as privacy amplification [15].

The basic reason that this arrangement can produce single photons with lower probability of multiple photons is that the delay system provides extra information about the photons produced. For instance, in the cases where one of the longer delays happened to cause the detector to fire, we know that all the prior delays did not cause the detector to fire. If the detection quantum efficiency is high, it is very likely that there were no photons in those modes coupled to those shorter paths. Thus  $P_{>1}$  is greatly reduced because it is just the multiphoton probability for only the last delay, rather than for all  $N_D$  of them, which has a mean photon number of  $\bar{n}$  vs  $\bar{n}/N_D$ .

We now quantify the advantage of this last scheme in its simplest and most straightforward implementation. We will see that this scheme results in the production of photon pulses where each pulse has its own individualized single-photon certification, and as expected, these certifications can be significantly better than the uniform result obtained from the conventional arrangement. To begin, we consider the standard PDC setup for producing heralded single photons. The trigger detector registers one photon of a pair and indicates the existence of the second photon exiting the correlated channel. The collection optics for that correlated channel are designed to collect, as close as can be approximated, just the photons correlated to those seen by the trigger detector. In this arrangement, both the trigger channel and output channel are set up to collect only one spatial mode of the field [16]. When the trigger detector fires, one photon has been received (assuming negligible dark counts), but we do not know if additional photons were also present as the considered detectors cannot distinguish a one-photon event from a multiphoton event. Given that the trigger detector has fired, the probability of  $n$  photons incident is

$$P_{\bar{n},\eta}^F(n) = \frac{[1 - (1 - \eta)^n] P_{\bar{n}}^-(n)}{\sum_{k=1}^{\infty} [1 - (1 - \eta)^k] P_{\bar{n}}^-(k)}. \quad (1)$$

Note that  $1 - (1 - \eta)^n$  is the probability of the detector firing for  $n$  photons incident and the detector quantum efficiency  $\eta$  is defined as the probability of the detector firing when just one photon is incident. We use Bose statistics for the probability  $P_{\bar{n}}^-(n)$  of having  $n$  photons emitted into a single mode of the PDC light, given  $\bar{n}$  [5,14]. Here we are considering the simplified case where the pump pulse duration equals the coherence time of the PDC light.

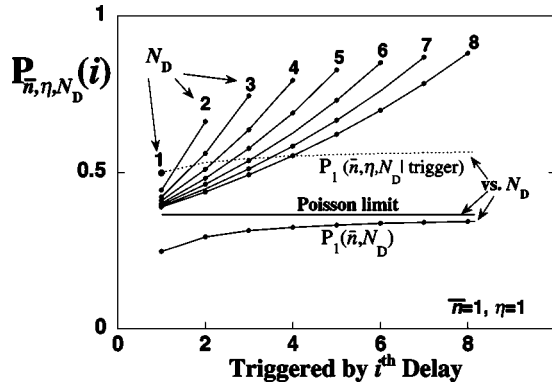


FIG. 2. The fan of curves labeled 1–8 are the probabilities of exactly one photon being produced given that the  $i$ th delay, in a system of  $N_D$  delays, caused the trigger to fire for  $\bar{n}, \eta = 1$ . The lowest curve is the total probability of a system of  $N_D$  producing a single photon per pump pulse with the Poisson limit shown just above. The dashed curve above the Poisson limit is the probability that the emitted light is a single photon given that the trigger did fire. (For these last three curves, the  $x$  axis is  $N_D$  rather than triggered delay.)

With this basis, we now describe a system with a number of delay lines of increasing length placed between the PDC crystal and the trigger detector. Each of these delay line channels intercepts a single, but separate, spatial mode of the field. The output channel collection optic is also modified to include the extra modes correlated to those of the additional trigger modes. Each of these trigger paths has a chance to cause the trigger detector to fire, with the shortest path providing the first chance, and the next longer path providing the next chance, and so on. But once the trigger detector fires due to a photon in a particular path, it cannot fire due to subsequent photons in the longer delay paths. The timing of the trigger detector firing relative to the pump pulse tells which delay path caused the firing. Thus the result of a single pulse of the pump laser is that either no trigger was produced or a trigger was produced and we know which delay path produced it. This last piece of information allows us to make a better determination of the probability that the photon produced was a single photon. If the photon that causes the trigger to fire is one of the later delay paths we will have a much lower likelihood of there being more than one photon. We now calculate this likelihood as a function of which delay path caused the firing.

For a system of  $N_D$  delay paths where the  $i$ th delay path caused the firing, the one-photon probability is

$$P_{\bar{n}, \eta, N_D}^-(i) = (1 - P_{\bar{n}/N_D, \eta}^E)^{i-1} P_{\bar{n}/N_D, \eta}^E (1) (P_{\bar{n}/N_D}^-(0))^{N_D-i}, \quad (2)$$

where  $P_{\bar{n}/N_D, \eta}^E$  is the probability that photons were incident if the detector did not fire. Then we use Eq. (1) with  $n = 1$  for a Bose distribution in each of the modes collected of Fig. 1(b). Figure 2 shows the functional form of these probabilities, where each line of the fan-shaped family of curves represents a system of  $N_D$  delays. Each point on a given line

corresponds to the trigger firing at a particular  $i$ th delay out of a set of  $N_D$ . The point's value is the “single-photon certification”—the probability of exactly one photon pair in the system. It can be seen that for sufficient  $N_D$ , and with high  $\eta$ , we can have emission events with single-photon probabilities around 90%, greatly exceeding the conventional arrangement results for the same  $\eta$  and  $\bar{n}$ . The standard PDC setup with one trigger path is the single  $N_D = 1$  point.

We have calculated two additional probabilities: the overall probability of producing a single photon [Eq. (3)], and that same probability given that the trigger did fire [Eq. (4)]. The first is obtained by taking the product of the probability of a particular delay event occurring and the probability of that event being due to a single photon and then summing over all possible types of events. Added to this is the probability for the case where no delays fire (so no heralding is present), but there is still a single photon (undetected) in one delay line. The second probability is obtained by eliminating the case where the trigger did *not* fire and renormalizing:

$$P_1(\bar{n}, N_D) = \bar{n} \left( \frac{N_D}{\bar{n} + N_D} \right)^{1+N_D}, \quad (3)$$

$$P_1(\bar{n}, \eta, N_D | \text{trigger}) = \frac{\bar{n} \eta \left( \frac{N_D}{\bar{n} + N_D} \right)^{1+N_D}}{1 - \left( \frac{N_D}{\bar{n} \eta + N_D} \right)^{N_D}}, \quad (4)$$

for a Bose distribution in each of the modes collected in Fig. 1(b). These two results are also shown in Fig. 2. For these curves, the abscissa is  $N_D$  rather than delay  $i$ . Note that the total single-photon probability  $P_1$  rises somewhat as  $N_D \rightarrow \infty$ . This probability, calculated for a thermal source, approaches the result that would be obtained for a Poisson distribution  $P_1(\bar{n}) = \bar{n} e^{-\bar{n}}$ , which is independent of  $N_D$ . The tending of the collection of many single-mode Bose subsystems toward the Poisson result is understandable, in that the more independent subsystems that are included in the sum, the more the individual events in the system are independent of each other, which is the definition of Poisson statistics. The higher values of  $P_1(\bar{n}, \eta, N_D | \text{trigger})$  seen in Fig. 2 indicate the advantage of having heralded photons, rather than those from a faint laser. We also note that for Poisson instead of Bose distributions, the above analysis yields qualitatively the same shaped curves seen in Fig. 2, but all the  $P_{\bar{n}, \eta, N_D}^-(i)$  probabilities are somewhat higher.

An analysis of Eq. (2) shows that  $\eta$  near 1 gives the best single-photon certifications. This is because high  $\eta$  means that the system provides more complete information about what has happened, e.g., an instance of the trigger not firing means with high certainty that no photon was incident, while low  $\eta$  decreases our certainty of that. Highlighting the advantage of this method, Fig. 2 also shows that in almost all cases, the multiplexed heralded system presented here significantly surpasses the single-photon probability of a faint

laser described by the Poisson limit to the curve. This advantage still holds for  $\eta < 1$ , although the certifications are not as high [13].

Equation (2) also shows that increasing  $\bar{n}$  increases the spread of the certifications, while decreasing the maximum single-photon certification possible. Thus there is a trade-off between having high-certainty single photons and high overall single-photon number. In fact,  $P_1$  does not continue increasing with increasing  $\bar{n}$ . The maximum occurs for all systems at  $\bar{n} = 1$ . This is the balancing point between reducing the number of single-photon events and increasing the number of multiple-photon events. This tells us the best rate to operate the system to maximize single-photon events, although it will not necessarily provide the highest single-photon certainties. We can still achieve higher single-photon certifications than is possible conventionally, while maximizing single-photon rates. We must of course verify that the events with high single-photon probabilities or certifications have reasonable likelihoods of occurring. An analysis of this question shows that while the likelihood of the later delay events occurring is lower than the earlier delay events, the dependence is not particularly strong. For instance, in the  $N_D = 8$ ,  $\bar{n} = 1$  case, the falloff from delay 1 events to delay 8 events is only a factor of  $\approx 2$ .

We have shown a way to decouple the probabilities of producing a single photon and the probability of producing more than one photon, using an array of parametric down-converters. By doing so, we can 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 [3,5]. In principle, this method could achieve an arbitrarily close approximation of a single-photon on-demand source. We have also analyzed a version that, while greatly simplifying the construction of an actual device, retains a significant amount of the benefit of the original concept. The setup would produce single photons with individual certifications that the photons produced are actually the desired single photons. Such a better-defined single-photon source will allow for better use of quantum channel resources in a cryptographic system by reducing the need for overhead tasks such as privacy amplification, as well as having implications for the field of quantum computation. As photon counting becomes more convenient at telecom wavelengths, we expect that integrated all solid-state implementations of these schemes will be made even easier, and we will have truly achieved the dream of a convenient source of single photons on demand. We are currently working on experimental implementations.

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