Fiber-assisted detection with photon number resolution

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We report the development of a photon-number-resolving detector based on a fiber-optical setup and a pair of standard avalanche photodiodes. The detector is capable of resolving individual photon numbers and operates on the well-known principle by which a single-mode input state is split into a large number (eight) of output modes. We reconstruct the photon statistics of weak coherent input light from experimental data and show that there is a high probability of inferring the input photon number from a measurement of the number of detection events on a single run. © 2003 Optical Society of America

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Many quantum information strategies require the preparation of nonclassical states. For example, the method of linear optical quantum computing proposed by Knill *et al.*[1] requires the preparation of single-photon states as well as maximally entangled photon multiplets. A number of schemes have been proposed for the preparation of such states, including single-photon emitters[2–4] and conditionally prepared photon pairs from parametric downconversion.[5–7] Conditional-state preparation requires the ability to distinguish states of different photon number, which is not possible with conventional photodetectors. Photon number resolution is also desirable for enhancing the security of quantum cryptographic schemes.[8,9] In this case it is important to resolve the photon statistics of the source at the sending and receiving stations.

There are several methods for constructing photon-number-resolving detectors. Among those demonstrated to date are the locally sensitive photomultiplier,[10] the superconducting bolometer,[11] and the superconducting transimpedance amplifier.[12] These detectors operate at cryogenic temperatures and have single-photon quantum efficiencies of approximately 20%, excepting the locally sensitive photomultiplier, which has an intrinsic quantum efficiency of up to 90%. On the other hand, conventional room-temperature APDs have intrinsic quantum efficiencies as high as 80%, although they respond only to the presence or absence of radiation. The ease of use of these devices suggests that it is worth exploring ways to develop the ability to resolve photons.

In this Letter we present an experimental detection scheme that implements a full photon-number-resolved measurement of light intensity for optical pulses. Our experimental setup follows the main idea outlined in Ref. 13. The input pulse is split into separate parts that are expected to contain no more than one photon. These photons are then detected with conventional APDs. The setup we describe here is constructed from only standard passive fiber-optic components, but it nevertheless permits the input pulse to be split into many time-delayed pulses while retaining a fixed number of output spatial modes. The design is depicted schematically in Fig. 1. The basic elements are 50/50 couplers and fibers of variable lengths. In the first step the input signal is divided into two signals that are launched into fibers of unequal lengths. These pulses become delayed with respect to each other, and their subsequent combination at another 50/50 coupler yields two pulses in each of the two output channels. By iterating this setup with delays twice as long as in the preceding situation, further doubling of the number of temporal output modes can be achieved. Thus the photon number of the incident pulse can be detected with only two APDs, if the time separation is ensured to exceed the dead times of the APDs. A less-efficient scheme with a single coupler and a fiber loop has also been investigated.[14]

For our implementation we used single-mode fibers at 780 nm (Lucent SMC-AO780B) to construct a detector with two stages, i.e., eight temporal modes. After the fiber setup, the pulses were separated in time by 108 to 164 ns. Without insertion losses the transmission through the complete fiber system was measured to be higher than 56%. A standard laser diode (Thorlabs V3-780-TO-DA) driven in pulsed operation at 777 nm served as a source of light with Poissonian statistics. These pulses had a width of approximately 14 ns and a repetition rate of 10 kHz. The detection of the attenuated signals at the fiber outputs was carried out with two standard APDs (Perkin-Elmer SPCM-AQR-13-FC), which are specified to have an efficiency of 66% and typical dead times of 50 ns. Hence the time bins with nonzero photons could be identified with a digital oscilloscope.

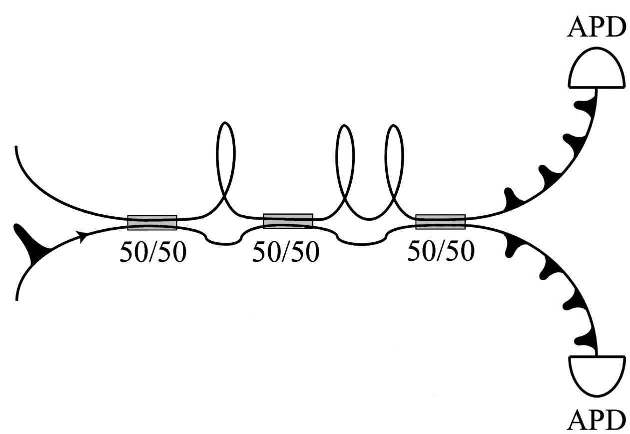

Fig. 1. Schematic setup of the detector. 50/50, symmetric fiber couplers.

A careful analysis of the measured data is crucial, since the raw statistics can emulate nonclassical properties such as sub-Poissonian photon number distributions. This is mainly because high photon numbers result in a nonnegligible probability that two photons remain together in one pulse and are counted as one. Therefore the number of stages of the fiber configuration essentially limits the incident photon numbers that can be reliably distinguished by the detector. The probability $p(k)$ of the detected counts is linked to the signal photon number distribution $\rho(n)$ by

$$p(k) = \sum_n p_{kn}(k \mid n)\rho(n)\,. \tag{1}$$

The photon number distribution can be reconstructed if the conditional probabilities $p_{kn}(k \mid n)$ of obtaining k counts for n incident photons are known. The exact values of $p_{kn}(k \mid n)$ depend on the detailed experimental setup, including nonideal 50/50 splitting and unbalanced losses. For known parameters of the fiber system they can be calculated by a basic stochastic model that takes into account the different possibilities for spreading the incident photons into the output modes. The inversion of the associated matrix allows the incident photon number distribution $\rho(n)$ to be identified from the measured distribution $p(k)$. For our detector with eight output pulses we expected a good performance only for distributions with mean photon numbers smaller than three. Hence we could restrict our data processing to $p_{kn}(k \mid n)$ with n smaller than eight, which yields an estimated error smaller than 1%.

To simplify the inversion, the influence of the convolution and the losses can be considered separately. This is equivalent to assuming that the probability of sending an input photon to all the output channels sums to one and introducing an overall loss factor. Our reconstructions of the photon number from the experimental data do not correct for losses, since these leave the form of the Poissonian distributions unchanged and reduce the means only. In addition, by not including the losses we demonstrate the potential capability of the detector to distinguish between different photon numbers if the transmission through the fibers is optimized and highly efficient detectors are available. Figure 2 shows our experimental results for coherent states with mean photon numbers of (a) 0.79 and (b) 2.00. The insets depict the actual count statistics that we obtained directly from the two APDs for samples of 10^4 single measurements. To eliminate dark counts and afterpulsing, we applied a temporal gating such that only counts within the expected time windows of 45 ns were accepted. The bars in the main graphs represent the normalized photon number distributions that we acquired from the detected data by inverting $p_{kn}(k \mid n)$. We determined the error bars shown by running 1000 Monte Carlo simulations for our measurement samples. The dots indicate the theoretical Poissonian distributions for the respective distributions with the same average photon numbers as the experimental data. The analysis reveals excellent agreement between experiment and theory for distributions with average photon numbers smaller than or equal to one [see Fig. 2(a)]. Moreover, as shown in Fig. 2(b), the direct inversion still works reasonably well for experimental data corresponding to a coherent state with a mean photon number of 2.00, although in this case negative probabilities may appear. Note, however, that we did not optimize the inversion in any way nor did we impose any constraints that would exclude negative probabilities.

We tested our inversion for increasing mean photon numbers with simulated Monte Carlo data for input Poissonian statistics, which we truncated at a photon number of eight. In this way we were able to confirm that direct inversion is possible only up to a mean photon number equal to two. The error in these reconstructions, based on the mean-square differences between the distributions, is 4.17×10^{-4}. The comparison of the experimental data with the simulated data revealed that the inversion is sensitive to events that measure counts with $k > 6$. These events cause negative probabilities to emerge in the photon distribution due to the inversion. Using advanced estimation techniques that exploit known probability properties should allow accurate reconstruction of distributions with higher mean photon numbers.[15] Following that line we investigated coherent states with averages as high as four. If we assume Poissonian distributions, we can estimate the mean of the detected data by a simple maximum-likelihood estimation, taking into account the conditional matrix $p_{kn}(k \mid n)$. With this approach we found good consistency between experimental data and the corresponding theoretical distribution for a mean photon number of 3.78, where

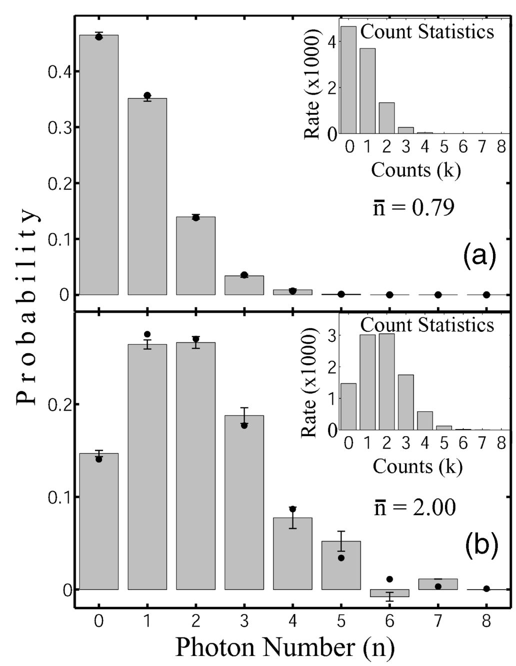

Fig. 2. Photon number statistics reconstructed by direct inversion of the measured data (see insets) from the fiber-based detector. The data (bars) show good agreement with the theoretical fits (dots) of a Poissonian distribution with the same mean photon number.

Table 1. Conditional Probabilities $\tilde{p}_{nk}(n = l\,|\,k = l)$ that l Counts are Triggered by l Photons for Poissonian Input Statistics with Average Photon Number $\bar{n}$ and Detector Efficiency η

	$\eta = 1$				$\eta = 0.7$			$\eta = 0.5$		
l	$\bar{n} = 0.25$	$\bar{n} = 0.5$	$\bar{n} = 1.0$	$\bar{n} = 1.5$	$\bar{n} = 0.25$	$\bar{n} = 0.5$	$\bar{n} = 1.0$	$\bar{n} = 0.25$	$\bar{n} = 0.5$	$\bar{n} = 1.0$
1	0.984	0.969	0.938	0.908	0.918	0.842	0.709	0.876	0.767	0.588
2	0.969	0.939	0.881	0.825	0.908	0.824	0.678	0.869	0.755	0.569
3	0.954	0.910	0.826	0.750	0.898	0.806	0.649	0.862	0.743	0.552

the deviations for all possible photon numbers summed to less than 0.012. Thus the photon-resolving detector proved to be a valuable tool for exploring quantum states in the photon number basis.

Generally speaking, there exist two main tasks for which photon-number-resolving detectors are needed. So far we have discussed one case, when the initial photon distribution is either unknown or—as in quantum cryptography—is to be confirmed by ensemble measurements. In the second case the incident state is well known from the beginning, and one wants to perform the detection of the photon number on a single-shot basis to address states individually. In such applications, e.g., conditional-state preparation,[5] the performance of the detector has to be evaluated on the confidence that l counts have actually been triggered by l photons. In our experiment this confidence can be characterized by the conditional probabilities $\tilde{p}_{nk}(n = l\,|\,k = l)$, which describe the probability that l photons cause l detection events. The $\tilde{p}_{nk}(n = l\,|\,k = l)$ always depend on the losses of the complete system as well as on the photon statistics, i.e., on the input state itself. To illustrate the reliability of our detector in such settings we calculated the relevant conditional probabilities for input Poissonian photon statistics and different losses (see Table 1). We found that a lossless detector with eight temporal modes allows appropriate discrimination of low photon numbers for coherent states with mean photon numbers as high as $\bar{n} = 1.5$. The distribution of the input light into a limited number of modes can therefore be tolerated if the ratio of maximum photon number to outgoing modes is sufficiently small. As expected, losses decrease the confidence for measurements on single quantum systems, which restricts the detector's use to photon number distribution with low-enough mean values.

In summary, we have demonstrated a fiber-based photon detector that is capable of resolving multiple photons. In our particular setup with eight temporal modes we could measure and recover the photon number statistics by direct inversion for coherent states with mean photon numbers as high as two. The design presented for the photon-counting detector can easily be extended to further split the incident pulse in time without the need to increase the number of spatial modes, which are monitored by the two APDs. Adding stages allows an increase in the reliability of the detector and permits the resolution of higher photon numbers. Because of the comparative simplicity of the setup, it is feasible to establish this photon-counting detector as a standard device in quantum optics. In the context of quantum information processing this is a step forward in implementing more-sophisticated schemes based on conditional state preparation.

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**Note added in proof*: After completion of this experiment, we became aware of very similar work performed independently.[16]

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