Many quantum information strategies require the preparation of nonclassical states. For example, the method of linear optical quantum computing proposed by Knill, Laflamme, and Milburn \(^1\) demands 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 \(^2, 3, 4\) and conditionally prepared photon pairs from parametric downconversion \(^5, 6, 7\). Conditional state preparation requires the ability to distinguish states of different photon number, which is not possible using conventional photodetectors. Photon number resolution is also desirable to enhance the security of quantum cryptographic schemes \(^8, 9\). In this case it is important to measure the photon statistics of the source at the sending and receiving stations. For implementations that use weak coherent states this is concealed by the noise of the detection mechanism. Hence the time bins with non-zero photons could be identified with an efficiency of 66% and typical deadtimes of 50 ns.

According to the quantum theory of photodetection, the signal obtained from an ideal noise-free detector has a discrete form corresponding to the absorption of an integer number of quanta from the incident radiation. In practice, however, the granularity of the output signal is concealed by the noise of the detection mechanism. When very low light levels are detected using devices with single-photon sensitivity such as photomultipliers or Geiger-mode operated avalanche photodiodes (APDs), the electronic signal can be reliably converted into a binary message telling us with high efficiency whether an absorption event has occurred or not. However, the intrinsic noise of the gain mechanism necessary to bring the initial energy of absorbed radiation to the macroscopic level completely masks the information on exactly how many photons have triggered that event.

There are several methods for constructing photon number resolving detectors. Among those demonstrated to date are the segmented photomultiplier \(^10\), the superconducting bolometer \(^11\), and the superconducting transimpedance amplifier \(^12\). These detectors operate at cryogenic temperatures and have single photon quantum efficiencies ranging from about 20% for the superconducting devices to approximately 70% in the case of the segmented photomultiplier. On the other hand, conventional room temperature APDs have intrinsic quantum efficiencies up to 80%, though they respond only to the presence or absence of radiation. The ease of use of these devices suggest that it is worth exploring ways to develop photon resolving capability.

In this paper, 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 \(^13\). The detection is done by splitting the input pulse into separate parts that are expected to contain no more than one photon and then detecting them with conventional avalanche photodiodes. The setup we describe here is constructed only from standard passive fiber optic components, but nevertheless permits the splitting into arbitrary 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 and launched into two fibers of unequal lengths, such that the partite pulses are delayed with respect to each other. Their subsequent combination at another 50/50 coupler then yields two pulses in each of the two channels. A second stage in which the relative delay is twice as long as the previous stage provides four pulses per output channel. Further doubling of the number of temporal output modes can be achieved by adding more stages. Thus the photon number of the incident pulse can then be detected using only two APDs, if the time separation is ensured to exceed the dead times of the APDs. A less efficient scheme using 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 ns 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 coherent states. 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 deadtimes of 50 ns. Hence the time bins with non-zero photons could be iden-
A careful analysis of the measured data is crucial since the statistics can emulate “non-classical” properties such as sub-Poissonian photon number distributions. This is mainly due to the fact that high photon numbers result in a non-negligible 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

$$p(k) = \sum_n p_{kn}(k|n)\rho(n). \quad (1)$$

The photon number distribution can be reconstructed, if the conditional probabilities $p_{kn}(k|n)$ of obtaining $k$ counts for $n$ incident photons are known. The exact values of $p_{kn}(k|n)$ depend on the detailed experimental setup including non-ideal 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 identification of the incident photon number distribution $\rho(n)$ from the measured distribution $p(k)$. For our detector with eight output pulses we only expected a good performance for distributions with mean photon numbers smaller than three. Hence we could restrict our data processing to $p_{kn}(k|n)$ with $n$ smaller than eight, which gives an estimated error being smaller than one percent.

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 reduces 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. Fig. 2 shows our experimental results for coherent states with mean photon number of 0.79 and 2.00 respectively. The insets depict the actual count statistics we directly obtained 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 we acquired from the detected data using the inversion of $p_{kn}(k|n)$. We determined the given error bars by running 1000 Monte Carlo simulations for our measurement samples. The dots indicate the theoretical fits 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 or equal to one (see Fig. 2a). Moreover, as seen in Fig. 2b, the direct inversion still works reasonably well for experimental data corresponding to a coherent state with mean photon number of 2.00, though in this case negative probabilities may appear. Note, however, that we did not optimize the inversion in any way nor did we put any constraints that would exclude negative
TABLE I: 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 different losses $1 - \eta$.

| $\bar{n}$ | $\eta = 1$ | $\eta = 0.7$ | $\eta = 0.5$ |
|---|---|---|---|
| 0.25 | 0.984 | 0.918 | 0.876 |
| 0.5 | 0.969 | 0.908 | 0.869 |
| 1.0 | 0.954 | 0.898 | 0.862 |
| 1.5 | 0.826 | 0.806 | 0.743 |
| 2.0 | 0.750 | 0.649 | 0.552 |

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 only possible up to a mean photon number two. The error in these reconstructions, based on the mean square differences between the distributions, is $4.17 \times 10^{-4}$. The comparison of the experimental data with simulated data revealed that the inversion is very 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 number $\bar{n}$. Following that line we investigated coherent states with averages up to 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 $p_{kn}(k|n)$. Using this approach we found good consistency between experimental data and the corresponding theoretical distribution for a mean photon number of 3.78, where the deviations for all possible photon numbers summed up to be smaller than 0.012. Thus the photon resolving detector proves to be a valuable tool to explore quantum states in the photon number basis.

Generally speaking there exist two main tasks where photon number resolving detectors are needed. So, far we have discussed one case when the initial photon distribution is either unknown or—like 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 $\mathbb{F}$, 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 describes 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 have calculated the relevant conditional probabilities for input Poissonian photon statistics and different losses (see Table I). We find that a lossless detector with eight temporal modes allows appropriate discriminations of low photon numbers for coherent states with mean photon numbers up to $\bar{n} = 1.5$. 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 usage of the detector to photon number distribution with low enough mean values.

In summary we have demonstrated a fiber based photon detector, which 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 up to two. The presented design 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 on stages allows both 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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