RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 48, NUMBER 2 AUGUST 1993

High-efficiency single-photon detectors

P. G. Kwiat, A. M. Steinberg, and R. Y. Chiao
Department of Physics, University of California, Berkeley, California 94720

P. H. Eberhard
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

M. D. Petroff
Rockwell International Corporation Science Center, 3370 Miraloma Avenue, Anaheim, California 92803

(Received 3 May 1993)

Using correlated photon pairs produced via spontaneous parametric down-conversion, we have measured the absolute single-photon detection efficiencies and time responses of four detectors: two solid-state photomultipliers (SSPM's) manufactured by Rockwell International Corp., and two custom-modified single-photon counting modules (SSPM's) manufactured by EG&G, Canada. The highest observed efficiencies were 70.9±1.9% (with an SSPM, at a wavelength of 632 nm) and 76.4±2.3% (with an SPCM, at 702 nm). We believe these to be the highest reported single-photon detection efficiencies in the visible spectrum; they are important for quantum cryptography and loophole-free tests of Bell's inequalities, as well as more prosaic applications such as photon correlation spectroscopy and velocimetry. We found that the time profile for coincidences between the SSPM and the SPCM consisted of a main peak with a 3.5-ns full width at half maximum (FWHM) preceded by a smaller peak by 11 ns. A similar time profile between two SPCM's displayed only one peak, with a 300-ps FWHM. Afterpulses were detected in the SPCM's at a level of less than 10^{-4} of the counting rate, with an exponential decay time constant of 4.5 μs.

PACS number(s): 03.65.Bz, 85.60.Gz, 89.70.+c

Recently there has been a growing interest in fast, high-efficiency single-photon detectors. High efficiencies are of course desirable in all applications relying on photon counting, such as photon correlation spectroscopy and velocimetry [1], optical time-domain reflectometry [2], and laser ranging [3], as well as in investigations of novel quantum-mechanical interference phenomena at the single-photon level [4]. However, they are absolutely *necessary* for practical implementation of various quantum cryptographic schemes, as well as in proposed loophole-free experiments to demonstrate violations of Bell's inequalities, which until recently required detection efficiencies greater than 83% (this limit has now been reduced to 67% [5]; see below). It is important to distinguish between single-photon detectors and certain photodetectors (e.g., *p-i-n* photodiodes), which may be very fast and display efficiencies greater than 95%, but which possess too much intrinsic noise to be useful at the single-photon level. The highest *single-photon* detection efficiencies to date have been observed using avalanche photodiodes in the Geiger mode; until now these have been limited to about 40%. We have measured efficiencies as high as 76%, and there are indications that these may be improved to 80% or even 90%. In particular, we describe herein a series of measurements made on a pair of solid-state photomultipliers (SSPM's) manufactured by Rockwell [6], and on a pair of single-photon counting modules (SPCM's) (Model SPCM-200-PQ) manufactured by EG&G [7]. The highest adjusted efficiencies measured were 70.9±1.9% and 76.4±2.3%, with an SSPM and SPCM, respectively. However, subsequent tests on the SSPM's revealed possible damage in the input fibers, and there were substantial reflection losses within the SPCM's. At present it is difficult to exactly specify the appropriate correction factors. Nevertheless, the results are very encouraging, with efficiencies nearly twice those previously reported. After discussing the need for high-efficiency single-photon detectors in quantum cryptography and loophole-free Bell's inequality experiments, we will review the two-photon technique for measuring absolute quantum efficiencies. The results for our detectors will be presented, along with relevant data on noise and saturation effects.

In the "one-time pad" scheme of classical cryptography [8], it is supposed that two collaborators wish to share a secret "key," a random number (or string of binary digits) with which they may encode and decode a message. Such a key may provide an absolutely unbreakable code, provided that it is unknown to any potential eavesdropper. The problem arises in key distribution: any classical distribution scheme is subject to noninvasive eavesdropping, e.g., using a fiber-coupler to tap the line without disturbing the transmitted classical signal. In the quantum cryptography proposals and demonstrations made to date, the security is guaranteed by using single-photon states [9] or very weak coherent-state pulses, with an average photon number much less than 1 [10]. The sender prepares each photon in a state of random, but definite, polarization (equivalently, some schemes use phase). The intended recipient measures the polarization (or phase) in a random basis. After repeating the process many times, the two then discuss publicly which bases were used for each measurement, but not the actual measurement results. The cases where different bases were chosen are not used for conveying the key, and may be discarded (or perhaps examined to detect the presence of an eavesdropper [11]), along with instances where the recipient detected no photon. In cases where the same bases were used, however, the participants will now have correlated information. From this, a random, shared key can be generated.

As long as single photons are used, and an eavesdropper does not know the basis in which a given photon was prepared, any attempt at eavesdropping will necessarily introduce errors due to the uncertainty principle. For if the eavesdropper uses the wrong basis to measure the polarization (or phase) of a photon before sending it on to the real recipient, the very act of measuring will disturb the original state. Because of the "no-cloning" theorem [12], there is no way to copy the original quantum state and make measurements on the duplicate [13]. By publicly comparing a subset of their correlated data (and subsequently discarding it), the collaborators may verify the security of their communication.

We have until now dealt only with perfect analyzers and detectors. Polarizers with cross-talk (or imperfect interferometers, for the phase example) and intrinsic noise within the detectors will introduce errors, and nonunity detection efficiency will increase the number of useless events where no photon was detected. Moreover, imperfect detectors will also require greater statistics to determine the presence of an eavesdropper, and place higher demands on any error-correcting codes. Clearly, high-efficiency, low-noise detectors are needed. Also, the data rate is obviously limited by the speed of the detectors.

While the cryptographic applications discussed above need high single-photon detection efficiencies to be practical, there is no intrinsic level below which the schemes categorically fail; in contrast, certain experiments on quantum nonlocality possess a specific efficiency cutoff—below this cutoff no rigorous tests may be made. It is well known that the predictions of quantum mechanics and those of any local realistic theory are different for certain experimental tests on correlated particles prepared in an entangled state. In particular, the quantum prediction violates Bell's inequality, which is satisfied by any local theory [14]. Nevertheless, to date all tests for violations of Bell's inequalities have been controversial, because the detection efficiencies have not been sufficiently high. The physical content of this "detection loophole" is as follows: If we only detect a fraction of the particles, it is possible that this fraction will mimic the quantum-mechanical predictions, even though the *entire* ensemble of particles still satisfies Bell's inequality. Local hidden variable theories which could explain all the results seen so far [15] have, in fact, been constructed. In all past experiments, auxiliary assumptions have been made, roughly equivalent to the assumption that the detected correlated pairs were representative of the emitted ensemble. No rigorous test is possible, however, as long as the detection efficiencies are low [16].

Although it was formerly thought that the lower limit on detector efficiencies necessary to close the detection loophole was 83% (assuming all other aspects of the experiment to be ideal) [17], recently two articles have shown how this may be lowered somewhat. By considering two-particle entanglements in which the amplitudes of the two terms are unequal, one of us (P.H.E.) has derived an inequality that requires only a 67% detector efficiency, in the limit of no background noise [5]. Taking a different approach, Braunstein and Mann [18] have also reduced the required efficiency by considering states of more than two correlated particles, a generalization of the three-particle example of Greenberger, Horne, and Zeilinger [19]. As the number of particles in the entangled state becomes large, the efficiency requirement can be reduced to 71%, also in the absence of noise. Our present results show that such efficiencies are realizable, and suggest that they may be made even higher.

The technique used to measure the absolute efficiency of a single-photon detector is now fairly well known. It was proposed by Klyshko [20], and first used by Rarity, Ridley, and Tapster [21] to characterize a silicon avalanche photodiode. Via the process of spontaneous parametric down-conversion in a crystal with a nonlinear susceptibility, it is possible to create pairs of photons that are highly correlated in time, and reasonably well collimated (i.e., constraining the direction of one photon of a pair determines within a few milliradians the direction of the other). One photon of each pair is directed to a "trigger" detector, and the collection optics are arranged to catch all of the "conjugate" photons with the detector whose efficiency is to be measured. See Fig. 1. The singles count rates at each detector (R_t and R_c) are measured, as well as the rate of coincidence counts (R_{tc}) between the detectors. In the ideal limit of no accidental counts (arising from photons from *different* pairs "accidentally" arriving within the coincidence timing window) and no background events (from unwanted external light, dark counts within detector, or electronic noise), the efficiency of the "conjugate" detector is simply the ratio of coincidence rate to the "trigger" detector singles rate: $\eta_c = R_{tc}/R_t$. In the presence of accidental counts A and the trigger detector background B, the formula is modified slightly:

$$\eta_c = (R_{tc} - A)/(R_t - B) \ . \qquad (1)$$

In practice our correlated photon pairs resulted from pumping a potassium di-hydrogen phosphate (KDP) crystal (cut for type-I phase matching) at 50.7° with respect to the optic axis. The down-converted photons typically exited the crystal at a few degrees with respect to the axis of the pump beam. Using irises and filters to select the trigger photons, we were able to measure the efficiency at the wavelength pairs 702–702 nm and 632–788 nm (the energies of the down-converted photons must sum to the energy of the parent ultraviolet photon at 351 nm). We examined four single-photon detectors: two SPCM's and two SSPM's. The former devices use Geiger-mode silicon avalanche photodiodes specially manufactured to have a very low "k," the ratio of hole- to electron-ionization coefficients [7]; our devices were also custom modified to employ a high overbias voltage of 30 V. The SSPM's are also silicon devices, but operate using impurity-band-to-conduction-band impact-

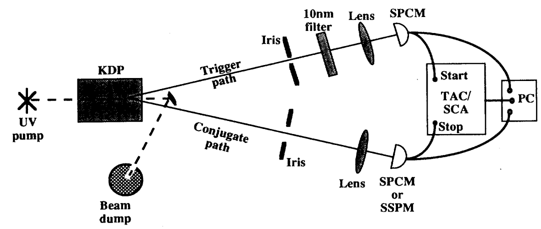

FIG. 1. A simplified schematic of the setup used to measure absolute quantum efficiencies. The 10-cm-long KDP crystal is pumped by the 351-nm line from an argon-ion laser. The smaller iris and interference filter on the path of the "trigger" photon serve (through phase-matching and energy conservation constraints) to define the path of the "conjugate" photons, which are all collected by the bottom detector (modulo losses en route). The outputs of the detectors are amplified and fed into the START and STOP channels of a time-to-amplitude (TAC) converter and single-channel analyzer (SCA). The coincidence rate output, as well as the two singles rates, are measured with a counter and stored on a personal computer (PC). By comparing the coincidence and trigger singles rates, the efficiency of the bottom detector may be determined.

ionization avalanches, yielding a very sensitive response in the infrared. The avalanches are localized within areas several micrometers in size, and do *not* in general lead to device breakdown, so that these devices are capable of distinguishing between single-, double-, etc., photon detections [6].

The efficiencies of the devices are listed in Table I. The results have been corrected for a number of systematic effects, principally the measured losses between the crystal and the conjugate detector (note that losses in the trigger photons do not affect the measured efficiency). For the SSPM's there is also a small upward adjustment to account for slightly nonoptimal biasing of the device, and at 633 nm a 12% correction factor to correct for an inappropriate timing window, which discarded coincidences from an unexpected precursor peak (see timing discussion below). Greater details of the exact measurement procedure and a fuller discussion of the various systematic effects are presented elsewhere [22].

It is important to note that associated with each of the detectors there are other sources of loss, *not* corrected for in Table I, which may yet be improved. Notably, the SPCM detector is housed in a can with uncoated glass windows, and the detector surface itself is broadband antireflection coated. Using multilayer, wavelength-specific coatings, it should be possible to essentially eliminate losses at these interfaces, implying a detection efficiency of greater than 82%. Moreover, the device bias was limited to 30 V over the breakdown voltage: a higher overbias is expected to increase the efficiency even further. (It might also worsen other device characteristics, such as dark count rate, however, so a careful study needs to be made prior to further speculation).

TABLE I. Corrected single-photon absolute detection efficiencies of two SSPM's and two SPCM's. The results listed include the improvements of a spherical retroreflection mirror on the SSPM's efficiencies. This served to reduce the effects of Fresnel losses [22].

Wavelength (nm)	Corrected efficiency (%) SSPM 1	SSPM 2	SPCM 1	SPCM 2
633	70.9 ± 1.6	69.5 ± 1.9	74.3 ± 2.0	65.0 ± 1.6
702		66.3 ± 1.4	76.4 ± 2.3	75.4 ± 1.5
788			53.7 ± 1.4	54.4 ± 1.0

In order to couple light into the SSPM's, which operate optimally only when cooled to about 6 K, it was necessary to use plastic optical fibers [23]. Evaluation of these input fibers after the efficiency measurements (and after dismantling the apparatus) revealed an unexpected loss of nearly 30%, which had not been present prior to the measurements. Correcting for *all* of the fiber losses would suggest SSPM efficiencies as high as $93\pm7\%$. At present there is no way to specify the exact correction factor for these effects, as it is not known when the damage to the fibers occurred. Work is currently underway to improve the fiber coupling scheme.

As mentioned earlier, in addition to high efficiency, a useful single-photon detector must have a low level of background, or noise. The SPCM's are internally cooled to about $-30\,^{\circ}$C, and have rather small active areas [only $(0.1\ \text{mm})^2$]; their dark count rates are correspondingly low, typically 65 s^{-1}. The SSPM's are cryogenically cooled to 6 K, but have much larger active areas [$(1\ \text{mm})^2$]; typical dark count rates are 7000 s^{-1}. Due to the passive quenching circuitry currently used with the SPCM's, they have an effective dead time of $\sim 1\ \mu$s, so that saturation effects become significant at counting rates of only 100 000 s^{-1}. [Future devices which employ active-quenching circuitry should have significantly higher saturation rates, and possibly less timing jitter (see below).] The SSPM's, on the other hand, do not rely on complete breakdown avalanches, and are expected to be continuously operating detectors for counting rates up to about 3×10^{7} s^{-1}. Our measurements of the SSPM dead time were limited to 50 ns, the size of an electronic blocking window external to the actual devices.

One common problem with standard avalanche photodiodes operating in the Geiger mode is the presence of afterpulses. After an avalanche, an impurity in the material may act as a trap for one of the carriers; a new avalanche can occur when the trap is emptied at some random later time, leading to an "echo" of the original signal. Such an afterpulse is obviously undesirable for accurate photon-counting applications, and could have given rise to a systematic error in our efficiency measurements. By performing an autocorrelation of an SPCM output with itself, we were able to measure the occurrence of afterpulses. (Again, a detailed discussion is given in [22].) We found that the fraction of afterpulses was less than 2×10^{-5} of the total number of counts. This value was calculated from our observation of a decaying-exponential distribution (time constant equal to 4.5 μs) of afterpulse probability. Other measurements by one of us (M.D.P.) suggest that the SSPM's are not susceptible to afterpulsing [24].

Previous measurements of the time correlation of the photon pairs have shown that they are emitted within 40

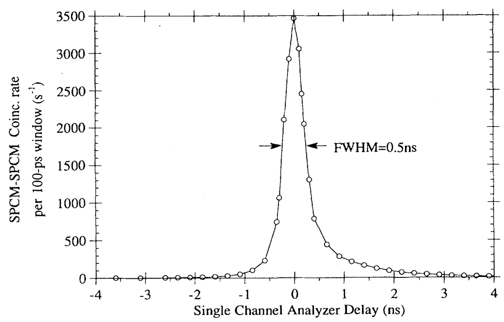

FIG. 2. Typical time-correlation profiles. Coincidences between two SPCM's, with singles rates of 70 and 250 KHz. The single-channel-analyzer window corresponded to 100 ps. Widths as low as 300 ps were seen at lower count rates.

fs of each other [25]. Therefore, they can be used to measure accurately the intrinsic time resolution of single-photon detectors, by mapping out the coincidence rate as a function of electronic delay time. A typical result, for two SPCM's, is shown in Fig. 2. The best time resolution observed in our experiments was also with two SPCM's, and possessed a single peak of full width at half maximum (FWHM) 300 ps, implying a single-detector response of 200 ps. A similar measurement performed with one SPCM and one SSPM displayed a double-peak structure: a "main" peak (FWHM equal to 3.3 ns), consisting of about 90% of the coincidence counts; and a smaller peak (FWHM equal to 4.5 ns), centered 11 ns *earlier*. The two-peak phenomenon is neither expected nor currently understood; we are considering possible causes.

In conclusion, we have demonstrated single-photon detection efficiencies nearly twice those previously reported. Furthermore, it should be possible to reduce certain losses associated with the detectors (e.g., housing windows, input fibers, etc.) to achieve even higher efficiencies. Results over 80% and 90% for the SPCM's and SSPM's, respectively, may be possible. With such improvements, one is definitely in the realm of feasibility for both practical cryptographic schemes and loophole-free tests of Bell's inequalities. As regards the latter, although one must clearly have some experimental "overhead," to allow for other losses and nonidealities, the present results are certainly encouraging about the possibility of performing a true test.

The SSPM's were developed at Rockwell Science Center, Anaheim; the specific devices used in the measurements reported here were prepared for UCLA as part of a DOE-sponsored program directed by M. Atac (of Fermilab and adjunct Professor of Physics, UCLA). We would like to thank Professor Atac for generously allowing the use of the SSPM's. We would also like to gratefully acknowledge the assistance of Bruce Johnson, and several helpful discussions with Dr. Robert McIntyre (EG&G, Canada). Three of us (P.G.K., A.M.S., and R.Y.C.) are supported by the U.S. Office of Naval Research under Grant No. N00014-90-J-1259. One of us (P.H.E.) is supported by the U.S. Department of Energy, Contract No. DE-AC03-76SF00098.

[1] H. Z. Cummins and E. R. Pike, *Photon Correlation Spectroscopy and Velocimetry* (Plenum, New York, 1977).
[2] G. Ripamonti *et al.*, IEEE J. Lightwave Tech. **8**, 1278 (1990); B. K. Garside, Photon. Spectra **22**, 79 (1988).
[3] *Proceedings of the 7th International Workshop on Laser Ranging Instrumentation,* edited by C. Veillet (OCA/CERGA, Matera, Italy, 1989).
[4] X. Y. Zou *et al.*, Phys. Rev. Lett. **67**, 318 (1991); P. G. Kwiat *et al.*, Phys. Rev. A **45**, 7792 (1992); T. S. Larchuk *et al.*, Phys. Rev. Lett. **70**, 1603 (1993).
[5] P. H. Eberhard, Phys. Rev. A **47**, R747 (1993).
[6] M. D. Petroff *et al.*, Appl. Phys. Lett. **51**, 406 (1987).
[7] A. W. Lightstone *et al.*, Electron. Eng. **61**, 37 (1989).
[8] G. Brassard, *Modern Cryptology: A Tutorial,* edited by G. Goos and J. Hartmanis, Lecture Notes in Computer Science Vol. 325 (Springer-Verlag, New York, 1988).
[9] A. K. Ekert, Phys. Rev. Lett. **67**, 661 (1991); C. Bennett *et al., ibid.* **68**, 557 (1992); A. K. Ekert *et al., ibid.* **69**, 1293 (1992).
[10] C. Bennett, Phys. Rev. Lett. **68**, 3121 (1992).
[11] S. M. Barnett and S. J. D. Phoenix, Phys. Rev. A **48**, R5 (1993).
[12] W. K. Wootters and W. H. Zurek, Nature **299**, 802 (1982).
[13] Note that if classical pulses are used instead, as from an attenuated laser, they must be sufficiently weak that the average photon number per pulse is less than 1, so that the probability of two photons in a pulse is much less than 1; otherwise, an eavesdropper could measure one of the photons, sending on the other, undisturbed photon.
[14] J. S. Bell, Physics **1**, 195 (1964).
[15] *Quantum Mechanics Versus Local Realism: The Einstein-Podolsky-Rosen Paradox,* edited by F. Selleri (Plenum, New York, 1988).
[16] There are also other loopholes to be overcome for a true test: the angular-correlation loophole discussed by Santos [E. Santos, Phys. Rev. A **46**, 3646 (1992)], and the rapid, random changing of the measuring-apparatus parameters [Y. Aharanov and D. Bohm, Phys. Rev. **108**, 1070 (1957); J. F. Clauser and M. A. Horne, Phys. Rev. D **10**, 526 (1974)]. Moreover, no experimental schemes used to date could close the detection and angular-correlation loopholes, even with perfect detectors. Elsewhere we discuss these problems and a possible remedy (unpublished).
[17] D. Mermin, Ann. N.Y. Acad. Sci. **480**, 422 (1986).
[18] S. L. Braunstein and A. Mann, Phys. Rev. A **47**, R2427 (1993).
[19] D. M. Greenberger *et al.*, in *Bell's Theorem, Quantum Theory and Conceptions of the Universe,* edited by M. Kafatos (Kluwer, Dordrecht, 1989), p. 73.
[20] D. N. Klyshko, Kvant. Elektron. (Moscow) **7**, 1932 (1980) [Sov. J. Quantum Electron. **10**, 1112 (1980)].
[21] J. G. Rarity *et al.*, Appl. Opt. **26**, 4616 (1987).
[22] P. G. Kwiat, A. M. Steinberg, R. Y. Chiao, P. H. Eberhard, and M. D. Petroff (unpublished).
[23] The plastic input fibers served as "cold filters" to absorb thermal infrared emissions, while providing high transmission of the down-converted photons.
[24] M. D. Petroff (unpublished).
[25] A. M. Steinberg *et al.*, Phys. Rev. Lett. **68**, 2421 (1992).