A Multichannel Detector for Photon Correlation

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Introduction

With the advent of the microchannel plate (MCP) photomultiplier tube (PMT), much attention has been given to the applications and performance evaluation (e.g., Oba *et al.*, 1979) of this device. The Hamamatsu R2519 photomultiplier tube is a MCP-PMT with a matrix of 100 anodes. Each individual anode can detect the photon events incident on a small corresponding region of the photocathode. Therefore, by making full use of these anodes, both temporal and spatial information of photon events can be picked up simultaneously. In analysing time-varying images such as speckle patterns and scintillation of starlight due to atmospheric turbulence, the space-time correlation can be measured and used to deduce certain features of both light sources and turbulent media (Dainty *et al.*, 1981). In this paper, we examine the operating performance of this MCP-PMT and present measurements of the detected autocorrelation and space-time correlation of a randomly varying speckle pattern.

MCP-PMT Evaluation

The Hamamatsu R2519 MCP-PMT has an S·20 photocathode with a maximum sensitivity of 64 mA W^{-1} at the wavelength of 420 nm. Its focusing method is electrostatic and the system magnification is 0.8. We have concentrated on several parameters which are important for photon correlation measurements. The evaluation results of these parameters are shown below.

Quantum Counting Efficiency (QCE)

The QCE is the combination of the quantum efficiency (QE) of the photocathode and the collection efficiency (CE) of both the focusing system and the MCP. The photons incident on the photocathode cause a certain number of photoelectrons to be emitted, dependent on the QE of the

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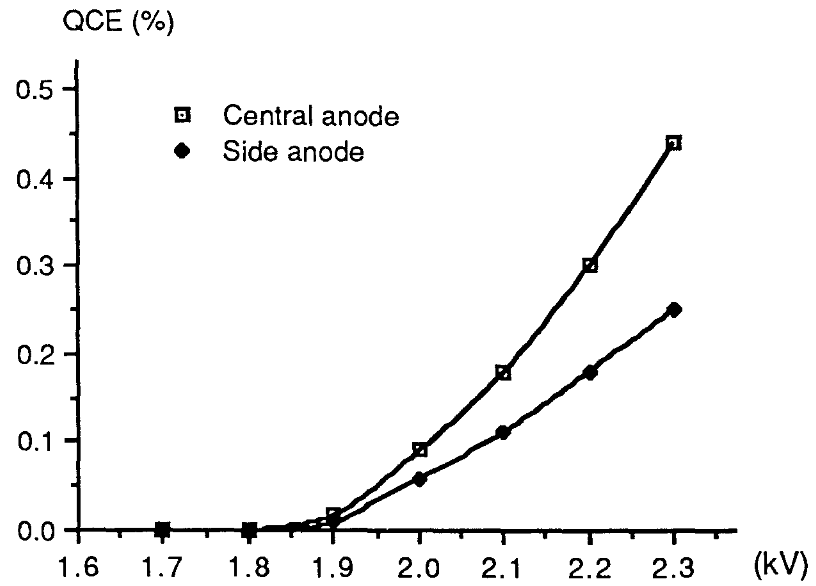

FIG. 1. Measured QCE versus voltage applied across the MCP at room temperature (18°C); the QCE of the central anode is slightly higher than that of an anode located at the side.

photocathode. Owing to inefficiencies of collection, a certain number of the photoelectrons are lost within the tube and only a fraction of the electrons are finally collected by the anodes. In our case, the QCE is found to be substantially lower than the QE of the photocathode. As Fig. 1 shows, the QCE was measured against voltage applied across the MCP for central and side-located anodes when the incident light was at the wavelength of 632.8 nm. At the typical operating point (2.1 kV), the QCE is about 0.16%, while the QE of the photocathode is given by the manufacturer as about 4.8% at this wavelength.

Dark Counts and Afterpulsing

Figure 2(*a*) shows that the dark counts are quite low, and that some of them can be removed by thresholding. For different anodes, the dark counts are slightly different. A low dark count may be achieved at the expense of low QCE and long dead time, as shown later.

Afterpulses are spurious output pulses that are time-correlated with the signal pulses. Afterpulses are generally of lower amplitude than the signal pulses and occur soon after the initiating pulses. A time autocorrelation peak can be observed in Fig. 2 (*b*) caused by the afterpulsing effect. This correlation function was measured using a very short sample time of 100 ns for the incident light field with Poisson statistics, which implies that the light field has constant classical intensity and has an autocorrelation value of zero. The maximum afterpulsing value (Brown *et al.*, 1987) $C(0)*N$, where $C(0)$ is the

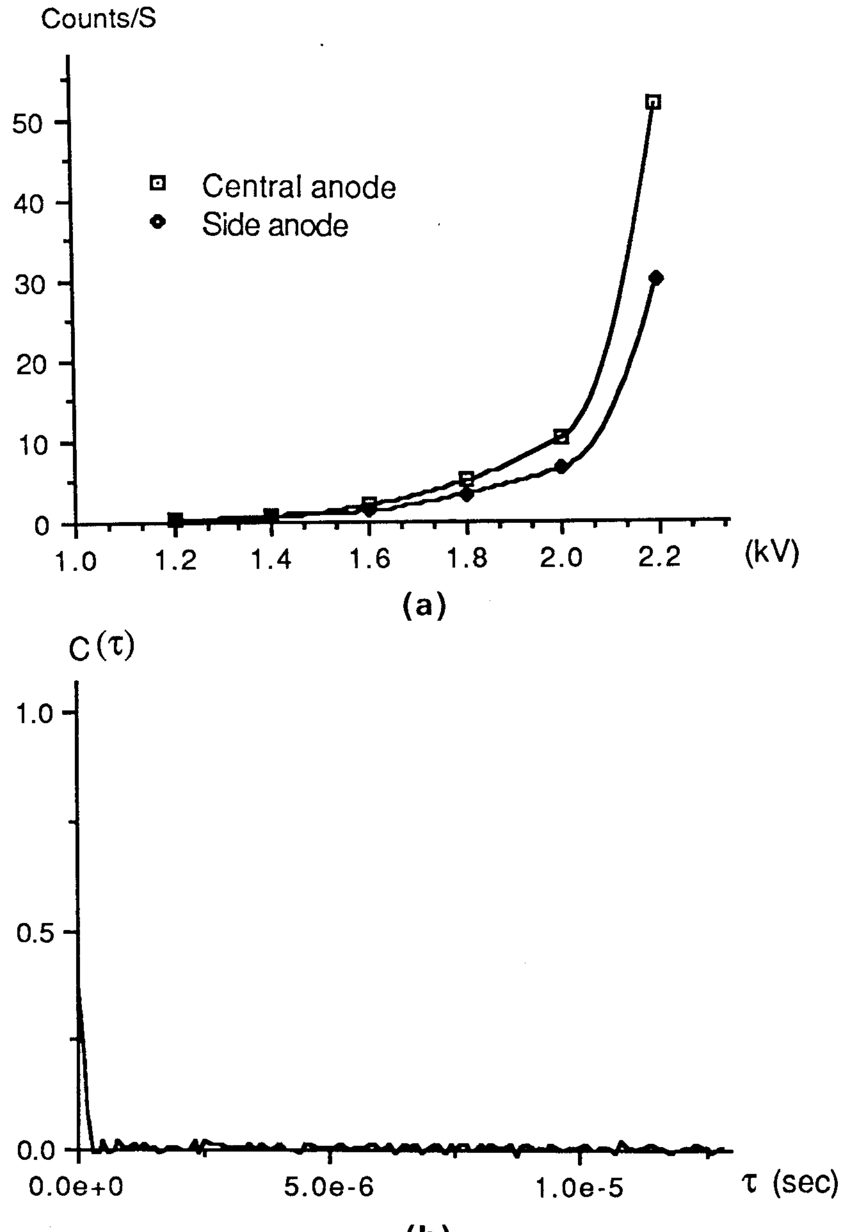

FIG. 2. (*a*) Dark counts versus voltage applied across the MCP at 18°C. (*b*) Correlation function showing afterpulse effect. Sample time 100 ns. Peak value is $C(0) = 0.38$. Average number of photon counts per sample time is $N = 1.1 \times 10^{-3}$.

peak value of the correlation function (normalized in the sense of equation (1) below) and N is the average number of photon counts per sample time, is found to be 0.042%, which is adequate for correlation measurements. The correlation length is spread over the first three channels of delay time, corresponding to 300 ns, or 3.3 MHz. Therefore, to avoid the afterpulse effect in correlation measurements, this tube should not be used to measure frequencies higher than 3 MHz.

Pulse Height Distribution

For an MCP-PMT operating in linear gain mode, the output pulse height distribution is exponential. This causes difficulties in choosing the threshold voltage of the discriminator, for example to eliminate low-amplitude noise afterpulses. To overcome these difficulties, it is necessary to operate in gain-saturated mode so that the smaller signal pulses are amplified to the same level as large saturated signal pulses while a gap still remains between the heights of signal and noise pulses. Therefore, all the signal pulses are expected to have similar pulse height at the output. By taking advantage of the difference between signal and noise pulses, a threshold voltage can be chosen to eliminate noise pulses and a higher signal-to-noise ratio can be obtained.

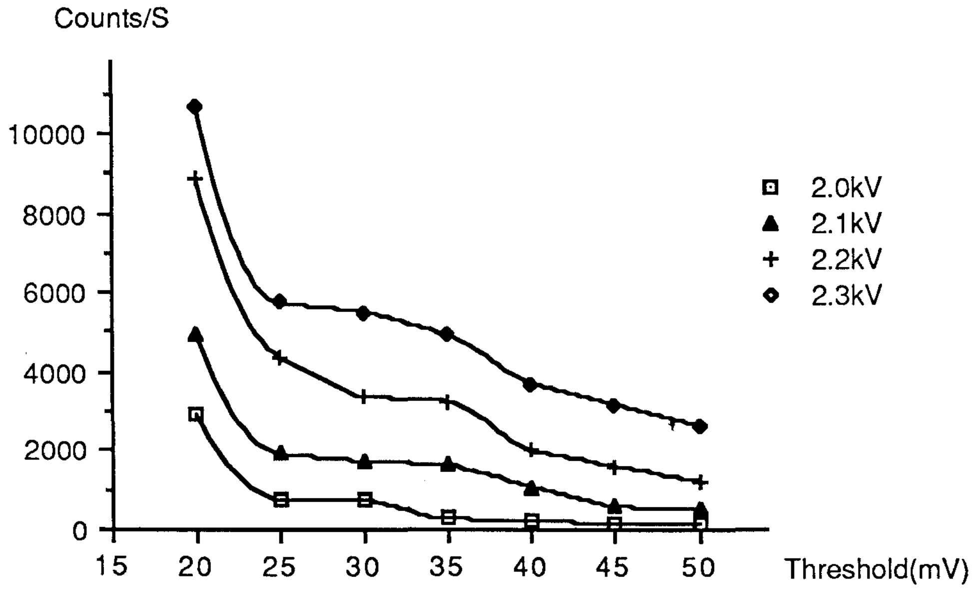

FIG. 3. Pulse counting rate versus discriminator threshold at various voltages applied across the MCP.

To evaluate the pulse-height distribution and obtain the best operating parameters, we measured the pulse counting rate versus voltage applied to the MCP for different threshold voltages of the amplifier/discriminator (Fig. 3). A fairly good pulse height distribution can be inferred from the fact the curve has a large plateau. This plateau should be taken as a reference for setting optimal operating parameters. In our case, an applied voltage of 2.1 kV for the MCP and a threshold voltage of 30 mV for the amplifier/discriminator are chosen as the best operating parameters.

Maximum Counting Rate

When the tube is operated in a photon-counting mode, the output counting rate decreases if the incident power is too high. Figure 4 shows the relationship between counting rate and intensity incident on the photocathode in the cases of white and red ($\lambda = 632.8$ nm) light. In both cases, the maximum counting rate was found to be 45 kHz.

It is found that the counting rate has a linear relationship with the incident power up to a rate of approximately 30 kHz. As the incident power increases,

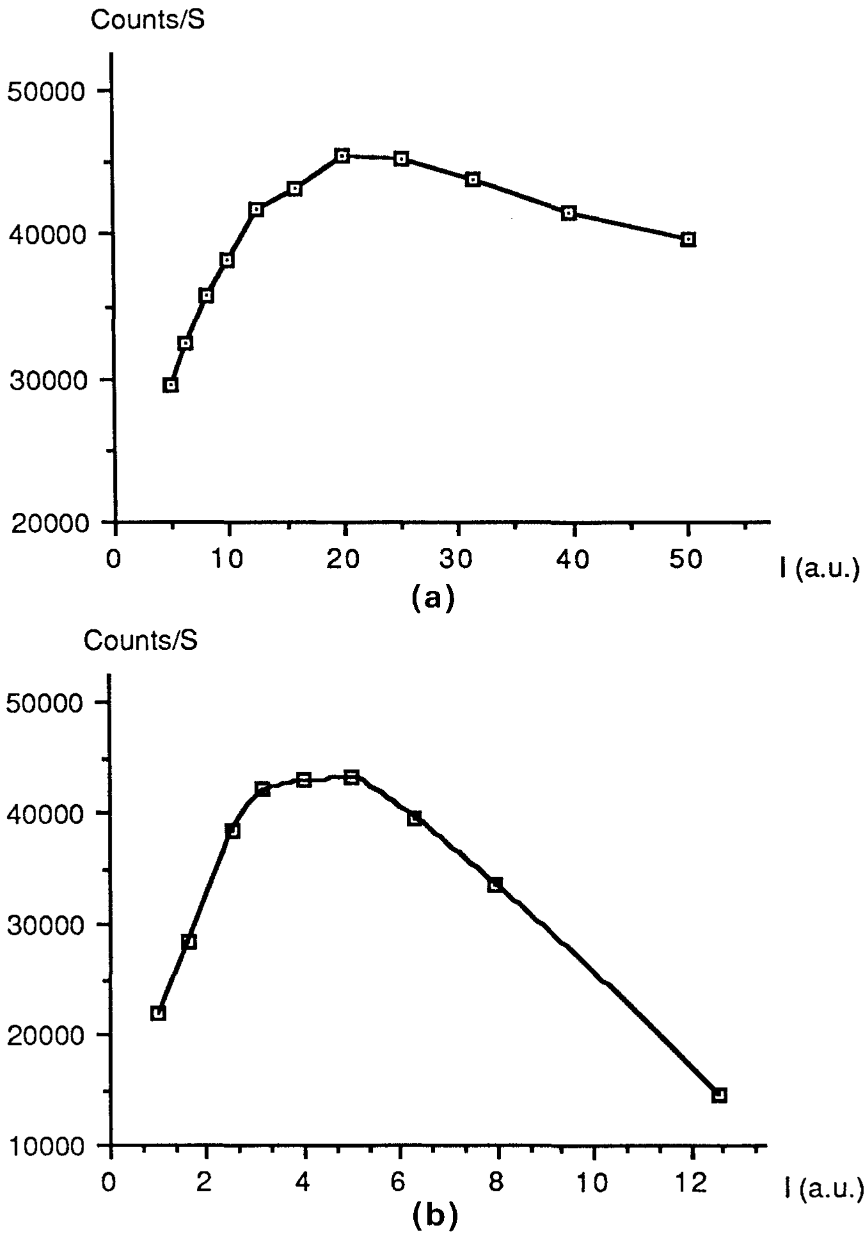

FIG. 4. Counting rate versus incident intensity for (*a*) white light and (*b*) light at $\lambda = 632.8$ nm.

the counting rate reaches a maximum and decreases thereafter because of the overlap effect. An incident power range which will keep the tube operated in a photon counting mode can be derived from the results. The range is rather small compared with that of an ordinary PMT.

Dead Time

The dead time of this MCP-PMT is significant owing to the fact that a long time is needed to restore the charge to the saturated channels of the MCP. The dead time was determined by measuring the photon-counting distribution $P(n, T)$, which is the probability distribution of counting n photons during the sample time T. A function

$$F(n) = (n + 1)P(n + 1, T)/P(n, T)$$

can then be calculated. It has been pointed out (Johnson *et al.*, 1966) that for coherent incident light with Poisson statistics and with the sample time T much longer than dead time τ,

$$F(n) = -(2N\tau/T)n + N(1 + N\tau/T)$$

where N is the observed average number of counts per sample time T. This relationship allows us to calculate dead time τ if N and T are known. Typical results are shown in Fig. 5, showing a measured dead time of about 4.4 μs.

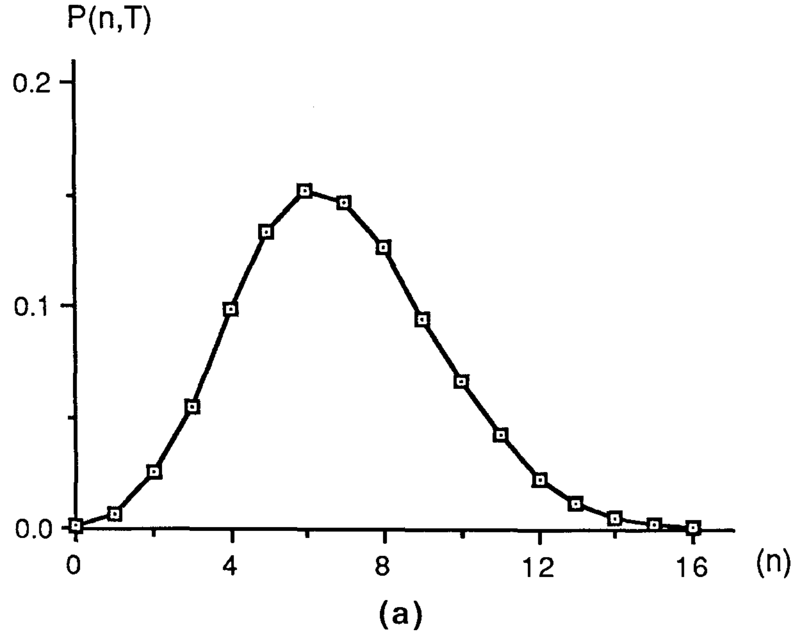

FIG. 5. (*a*) $P(n, T)$ measured with sample time 2.0×10^{-3} s and average number of counts per sample time, $N = 6.8$.

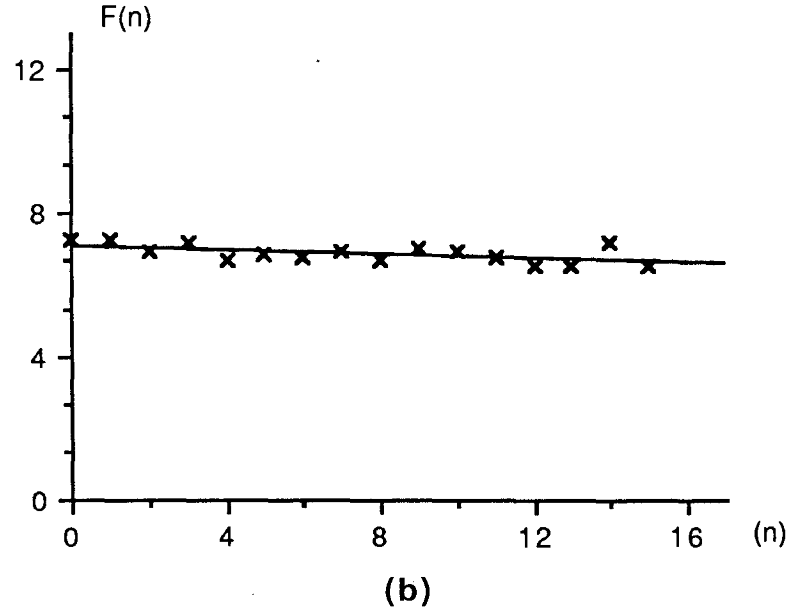

FIG. 5. (*b*) $F(n)$ calculated from $P(n, T)$ giving a best fit to the line $F(n) = 0.03\,n + 7.12$. The implied dead time is $\tau = 4.4\ \mu s$.

Cross-talk

When the photocathode is illuminated by light restricted by a fine pinhole to cover a small area corresponding to one anode, signal pulses are detected not only from this anode but also from the adjacent anodes. The cross-talk is defined as the ratio of signals detected from adjacent anodes to that from the illuminated anode. There are two main causes of cross-talk: one is the spreading of photoelectrons inside the tube, the other is the capacitance between the anodes. The measurement shown in Fig 6(*a*) was made by scanning a pinhole image across the photocathode and recording the photon counts in a single anode.

The result indicates that the anode is collecting signals from a circular area of about 2 mm diameter at the photocathode. The spatial averaging effect, as discussed later, may severely degrade the contrast of a measured correlation function. In addition to the source of cross-talk mentioned above, the capacitance between anodes also gives rise to cross-talk. As Fig. 6(*b*) shows, the cross-correlation between two adjacent anodes was measured at a very high sampling frequency (2 MHz). The incident light was spatially uniform and had Poisson statistics so that the light field did not itself introduce cross-correlation between the two channels and the observed correlation was that between the original signal from one anode and the capacitance-induced signal from the other anode. There appears a sharp peak at very high frequencies and a rather long tail. This peak covers the first two channels of

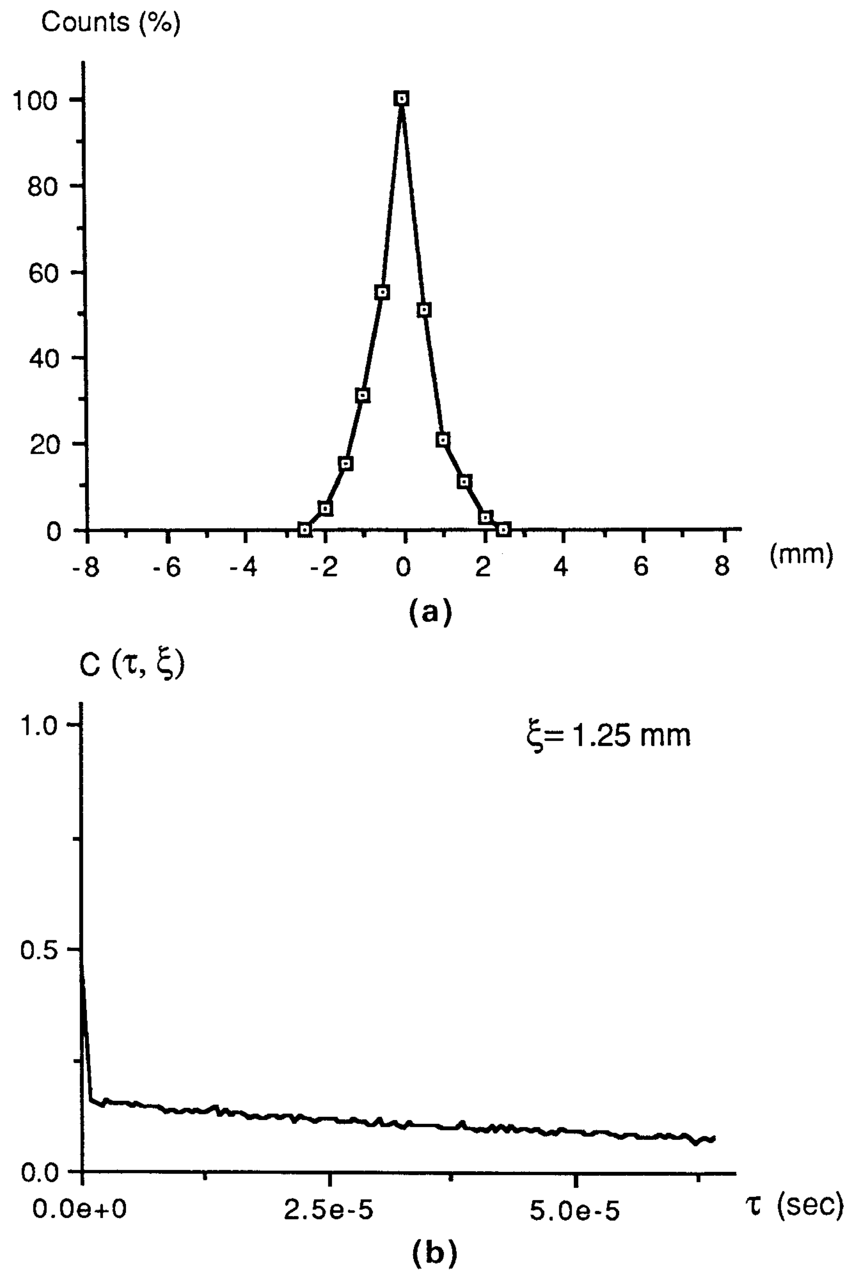

FIG. 6. (*a*) Result of scanning a 0.2 mm diameter pinhole image across photocathode; (*b*) cross-correlation with Poisson incident light beam showing capacitative cross-talk.

delay time, which corresponds to a frequency of 1 MHz. It is therefore clear that the capacitance between anodes is quite large and capacitance-induced cross-talk becomes dominant at frequencies above 1 MHz.

PERFORMANCE OF MCP-PMT ON PHOTON CORRELATION MEASUREMENTS

We are using this MCP-PMT to measure the correlation function of time-varying images. By considering the statistics of the secondary emission

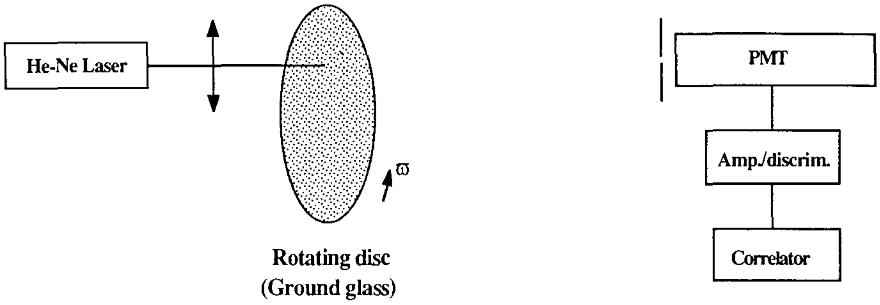

FIG. 7. System for measuring correlation functions.

process for a random incident light field, the following equation can be derived (Jakeman, 1973).

$$\frac{\langle n(t, T)n(t+u, T)\rangle}{\langle n\rangle^2} = \frac{\langle I(t, T)I(t+u, T)\rangle}{\langle I\rangle^2}, \quad u \neq 0 \qquad (1)$$

where $n(t, T)$ is the photon counts at time t over a period of T, $I(t, T)$ is the intensity at time t, and u is the time delay. The angle brackets represent an ensemble average.

Equation (1) has a very important implication: an unbiased estimate of the intensity correlation function can be obtained by means of correlating photon counts. In our case, the MCP-PMT is used to count photon events and these counts are then correlated by a digital correlator (Langley-Ford DC128). By making full use of an array of anodes, both autocorrelation and space-time correlation can be measured. The experimental setup is shown in Fig. 7; the correlation function of the speckle pattern produced by a rotating disc is measured at far field by the MCP-PMT system.

The results are shown in Fig. 8. As mentioned earlier, the contrast was severely degraded by the finite detecting area. Figure 8(*b*) shows that the contrast could be enhanced to unity by mounting a pinhole over one element. Figures 8(*c*) and (*d*) shows the cross-correlation in the x and y directions. Two dimensional cross-correlations can be easily determined by the tube. A zoom lens can be mounted in front of photocathode to adjust the distance between the two points to be measured.

CONCLUSIONS

The performance of this tube for photon correlation has been evaluated. In general, its main advantage is that both spatial and temporal information can be measured with a single tube. The tube also has a good pulse height distribution and low dark count if it is operated optimally.

The main drawbacks of the device are due to the fundamental characteristics of the MCP, such as long dead time and low detection efficiency.

Together with the long dead time, both afterpulsing and cross-talk limit the tube to measurement of frequencies up to 1 MHz. Furthermore, the finite detection area can severely degrade the contrast of photon correlation functions. This can be overcome by mounting a pinhole array in front of the photocathode.

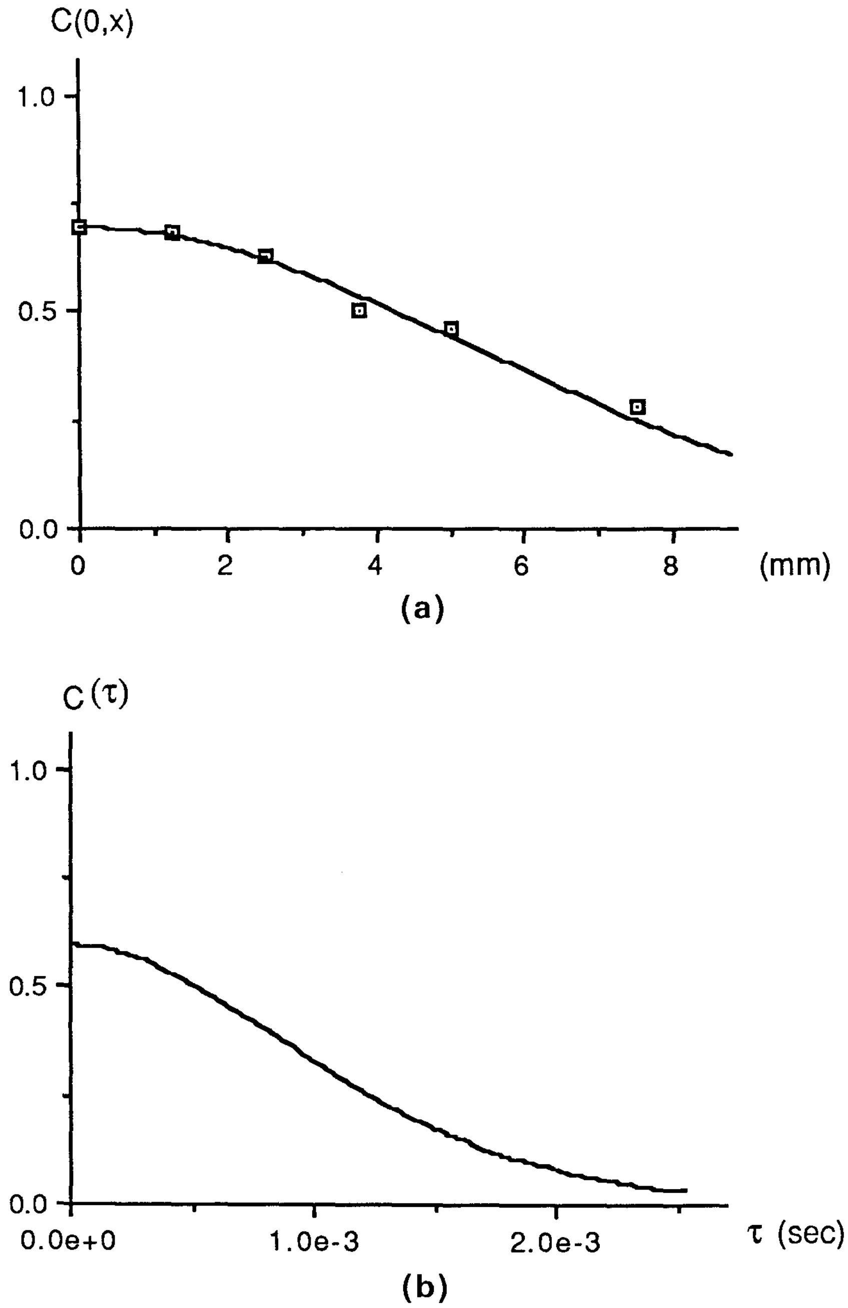

FIG. 8. (*a*) Temporal correlation function measured using the MCP-PMT; spatial averaging has degraded the contrast $C(0)$. (*b*) Temporal correlation determined by placing a small pinhole over the photocathode; the contrast $C(0)$ increases to unity.

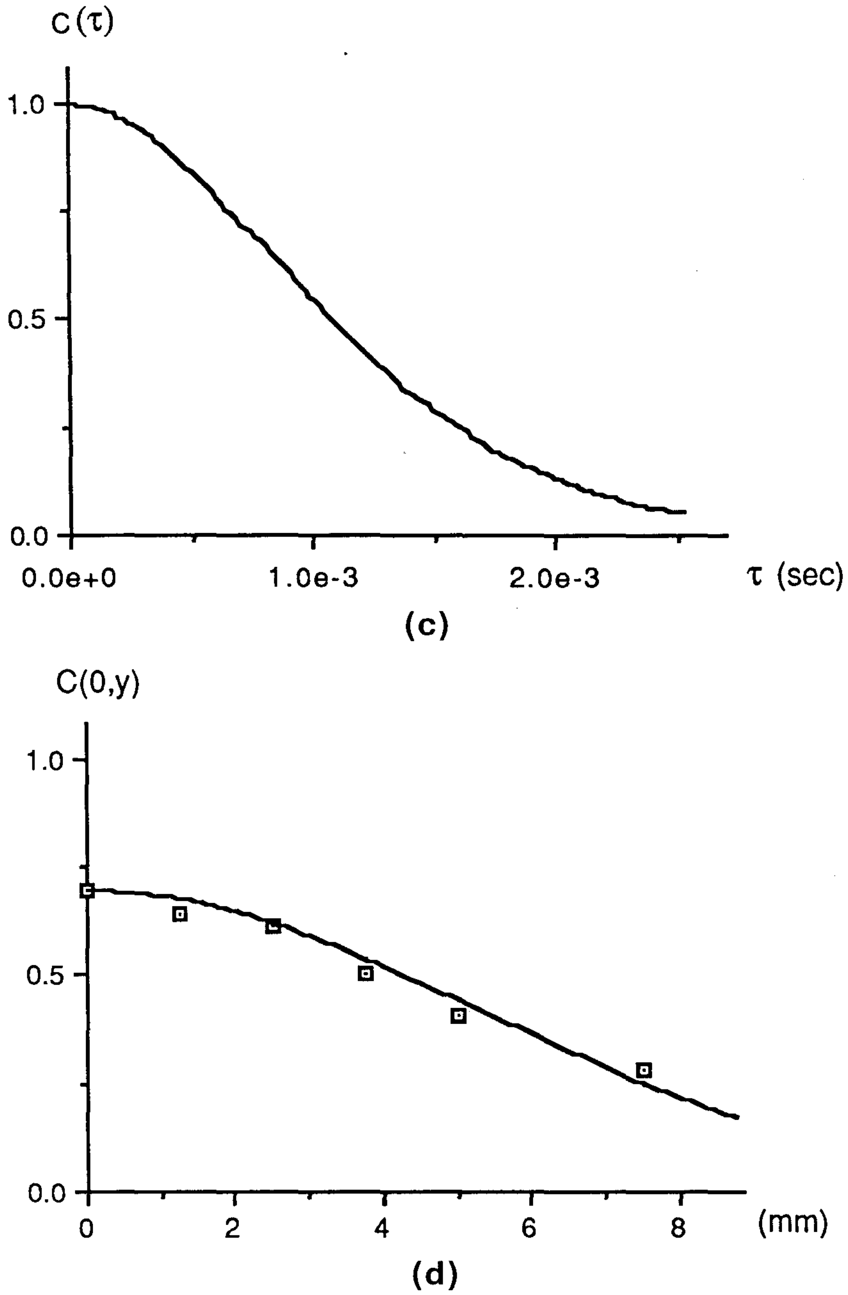

FIG. 8.(c) The spatial correlation in the x-direction. (d) The spatial correlation in the y-direction.

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