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Photon detection with cooled avalanche photodiodes

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Commercial avalanche photodiodes have been operated as single-photon detectors at an optimum operating temperature and bias voltage. These detectors were found to be 1.5–3 times more sensitive than presently available photomultiplier tubes (PMT's). Both single-photon detection probability and detector noise increase with bias voltage; detection probabilities greater than twice that of a PMT were obtained with detector noise levels below 100 counts per second. Higher probabilities were measured at higher noise levels. The sources of noise and their dependence on temperature and bias voltage are discussed.

Recent work has indicated that avalanche photodiodes (APD's) can be used as high-gain detectors for low-light-level applications, such as optical communications or remote sensing.[1,2] APD's have inherently high gains as well as the reliability and small size of solid-state devices; however, they suffer from much higher thermal noise than photomultiplier tubes (PMT's) at similar operating temperatures. Here we report experimental test results of commercially available APD's operated in a single-photon detection mode. While in this mode, APD sensitivities greater than those available with PMT's were achieved at comparable noise levels.

When an APD is cooled to reduce the number of thermally generated carriers in its active region, it can be reverse biased beyond its breakdown voltage and held in this overbiased state. In this state, a photon incident on the diode junction can initiate an "avalanche" of charge carriers, creating a detectable signal.[3-6] The device has a very high (10^7–10^8) internal gain, and it can be used to detect single photons.

The APD's tested are RCA type C30902S infrared-sensitive silicon diodes. These devices are selected by the manufacturer for performance as photon counters, and they are sold as "optimized" for photon counting at room temperature, with dark counts typically greater than 15 kHz per second and detection probabilities of 5% at 830 nm.

The APD to be tested was cooled to between 77 K and room temperature by a Joule–Thomson cooler inside a small evacuated chamber and illuminated with a laser diode emitting at 822 nm. The laser intensity was monitored by a United Detector Technology optical power meter before being attenuated to a few photons per laser pulse by calibrated neutral density filters. Then a second beamsplitter divided the beam between the APD and the PMT. The PMT was an RCA model C31034 with a GaAs photocathode. It was cooled to about -30 °C and was operated at a gain of approximately 10^6. A schematic of the optical setup is shown in Fig. 1. All optical components were contained in a dark enclosure.

In these tests the APD was restored to its bias voltage passively after each avalanche event by a resistor in series with the diode. Using this circuit, the recovery time of the detector was approximately 6 μs.

The frequency of dark noise counts was measured for each diode as a function of temperature and reverse bias voltage, and dark counts were measured for the PMT. These data were collected simply by counting noise events with a time-interval counter and reading and storing the count data with an IBM AT. Measurements were made at temperatures between 77 K and room temperature. At intermediate temperatures, the rate of occurrence of dark counts from the APD's increased more slowly with increasing bias voltage than it did at higher and lower temperatures. The optimum operating temperature for these devices appears to be about 200 K. At this temperature, the dark noise counts were less than 100 per second for bias voltages as high as 10 V above the breakdown voltage. Operating the detector at the highest possible bias voltage is desirable to obtain the highest detection probability. To measure the APD detection probabilities, the APD was illuminated with a laser diode modulated at 15 kHz with a pulse width of 50 ns. The probability of single-photon detection was taken as the ratio of the number of photons detected per second by the APD to the number of photons per second incident on its active region. Two PMT's and a photodiode power meter were used as independent calibration detectors to determine the intensity of incident light on the APD. From measured intensities and calibrated

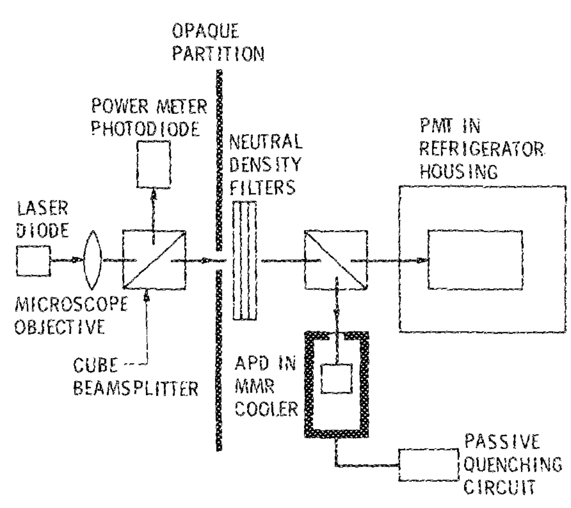

FIG. 1. Arrangement of optical components inside the dark enclosure.

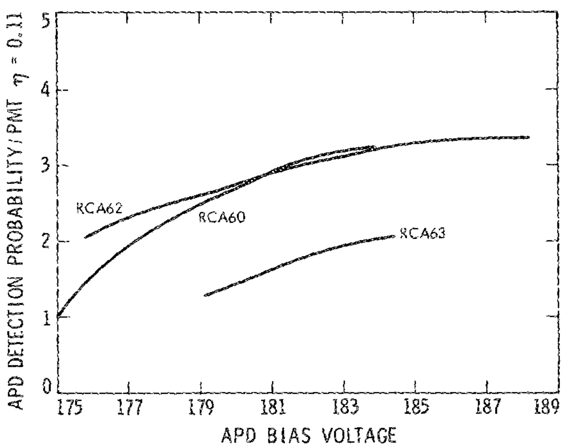

FIG. 2. Ratio of APD detection probability to PMT quantum efficiency as a function of APD bias voltage.

optics, the number of photons falling on the APD during each laser pulse was calculated. The uncertainty in this measurement was about 30%, due mostly to uncertainties in the manufacturer's specifications of the quantum efficiencies of the PMT's.

When the APD is used in this Geiger mode of operation, false avalanches are generated by electrons from previous avalanches trapped in the crystal lattice which dislodge after varying time intervals. In order to quantify the rate of these false occurrences from the APD, a coincidence circuit was incorporated into the test setup. Voltage trigger pulses from the laser power source were used to gate this logic circuit which transmits either the APD output counts occurring during a laser pulse ("true" counts), those occurring outside a laser pulse ("false" counts), or all output counts.

Using the true-count detection data, a single-photon detection probability was calculated for each applied voltage. The ratios of the APD detection probability to the PMT quantum efficiency [$\sim$0.11 at 822 nm, when cooled to $-30\,^{\circ}$C (Ref. 7)] for the three diodes tested are plotted in Fig. 2 as functions of APD bias voltage. The uncertainty in these curves is less than 3%. For a false-count rate or effective dark-count rate of 100 counts per second and an overbias of about 1.5 V, single-photon detection probabilities were greater than that of the PMT for all three diodes tested. At 1.5 V overbias, diode 62 exhibited a probability of detection of approximately 25%, over twice the quantum efficiency of the RCA C31034 PMT. Two of the diodes tested were found to have single-photon detection probabilities that approached 38% for a 10-V overbias; however, at this bias voltage the effective dark-count rate nearly equals the signal-count rate.

False-count rates for the three diodes tested are plotted as functions of detection probability in Fig. 3. As can be seen

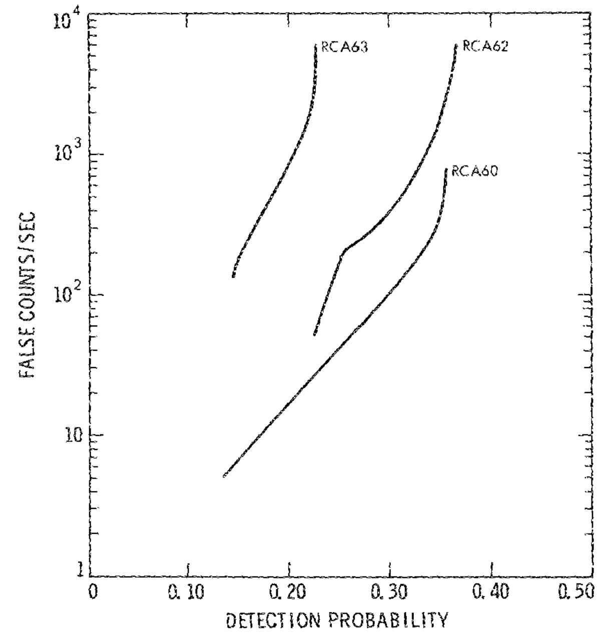

FIG. 3. Noise counts per second as a function of single-photon detection probability.

in the figure, false-count rates increased rapidly as the overbias was increased. Very good signal-to-noise ratios were observed with diode 60: at a detection probability of 20%, it gave only about 20 false counts per second. Even at high probabilities of detection, false counts remained low: the false-count rate was below 100 per second for detection probabilities up to 30%.

In summary, single-photon detection with optimally cooled avalanche photodiodes has been demonstrated with probability-of-detection values ranging from 1.5 to 3 times that of the PMT. At detection probabilities of up to 30%, false- and dark-count rates of less than 100 Hz were observed. For applications requiring small, reliable, highly efficient photodetectors, such as optical communication over planetary distances, cooled APD's may provide a very attractive alternative to presently used PMT's.

[1]D. Robinson and B. Metscher, TDA Progress Report, Jet Propulsion Laboratory, Pasadena, CA, 42-87, p. 41, 1986.
[2]D. Robinson and B. Metscher, in *Proceedings of the Society of Photo-Optical Instrumentation Engineer's Optoelectronics and Laser Applications in Science and Engineering Conference*, edited by R. J. Caswell (SPIE, Bellingham, Washington, 1987), Vol. 750, pp. 32–36.
[3]R. McIntyre, IEEE Trans. Electron Devices **ED-19**, 703 (1972).
[4]R. McIntyre, IEEE Trans. Electron Devices **ED-20**, 637 (1973).
[5]P. Ekstrom, J. Appl. Phys. **52**, 6974 (1981).
[6]W. Oldham, R. Samuelson, and P. Antognetti, IEEE Trans. Electron Devices **ED-19**, 1056 (1972).
[7]M. Cole and D. Ryer, Electro-Opt. Syst. Des. **4**, 16 (1972).