A Cooled Avalanche Photodiode With High Photon Detection Probability

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An avalanche photodiode has been operated as a photon-counting detector with 2 to 3 times the sensitivity of currently-available photomultiplier tubes. APD detection probabilities that exceed 27% and approach 50% have been measured at an optimum operating temperature which minimizes noise. The sources of noise and their dependence on operating temperature and bias voltage are discussed.

I. Introduction

The use of optical wavelengths for communication over planetary distances requires detectors sensitive enough to detect light pulses containing only a few photons. Presently the only detectors with high enough gain and low enough noise to be useful for detecting such faint signals are photomultiplier tubes (PMTs); however, their low quantum efficiency, the fragility of vacuum tube packages, and the high anode voltages required are important disadvantages for a space-based optical receiver. As a possible alternative, avalanche photodiodes (APDs) have been tested in a single photon detection mode. When cooled to reduce the number of thermal carriers, an APD can be reverse-biased beyond its breakdown voltage to give it a very high (10^7 to 10^8) internal gain. APDs have a higher quantum efficiency and the reliability of solid state devices; thus they may be a useful alternative to PMTs.

The theory of operation, statistical models of signal detection and noise generation, and quenching systems have been investigated by others (Refs. 1–6). The present work centers on understanding the operational characteristics of APDs in a photon counting mode, and in particular on measuring the probability of photon detection as a function of temperature and bias voltage.

The theory of operation of APDs, the sources of noise, and the problem of quenching have been discussed in previous work (Ref. 7). The experimental procedures used to examine the characteristics of APDs and to measure detection probabilities are described here. Experimental results are then presented and discussed.

II. Experimental Setup and Procedure

A schematic of the experimental setup is shown in Fig. 1. The APD is cooled in an MMR Technologies K7701 System I microminiature refrigerator, in which the diode is mounted on a cold finger inside a small evacuated chamber and connected to the quenching circuit by manganin wire leads. The light source is a Mitsubishi ML-3101 laser diode emitting at 822 nm at 20 mA operating current. The laser may be operated as either a pulsed or a continuous source. A calibrated beamsplitter directs a known fraction of the laser light to a United Detector Technology S550 optical power meter to monitor the light level incident on the detector being tested. The light intensity is attenuated to a few photons per laser pulse by neutral density filters calibrated at 822 nm, then a second beamsplitter divides the beam between the APD and PMT. Two different PMTs were used, an RCA model C31034 and an RCA C31034A-02, both with GaAs photocathodes. These were cooled to 240 K in a TE refrigerator housing and were operated at 1600 V. All optical components were contained in a light-tight enclosure. Data collection and reduction were accomplished using a pair of HP 5370A time interval counters, a Tektronix 7834 storage oscilloscope, and an IBM PC AT (Fig. 2).

The APDs tested were RCA type C30902S IR-sensitive silicon diodes. This model is similar to the one tested in previous work (Ref. 7; RCA C30817), but the C30902 diodes are selected by the manufacturer for performance as photon counters and are sold as "optimized" for operation in a photon counting mode.

The APDs were tested using a passive quenching circuit shown schematically in Fig. 3. The recovery time of the detector using this circuit, i.e., the time between a detection event and restoration of the bias voltage across the diode to its original value, was approximately 6 μs.

An active quenching circuit devised by Cova, et al., (Ref. 5) was built and tested, but effective implementation of their discrete-component, high-frequency feedback circuit proved impractical. However, since active quenching can reduce the detector's dead time to as little as 10 ns, further consideration of active quenching circuits is planned.

The frequency of dark noise counts was measured for each diode as a function of temperature and reverse bias voltage, and dark noise was measured for the PMT. These data were collected by simply counting noise events with a time interval counter and reading and storing the count data with an IBM PC.

To measure the APD detection probabilities, the light source was pulsed at 15 kHz with pulses of about 50 ns duration. The voltage pulse from the laser power source was used to gate a logic circuit (Fig. 4) 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.

The PMT measured the beam intensity after attenuation. From this measurement, using the quantum efficiency of the PMT and the measured efficiency of the beamsplitter and other optics, the light intensity incident on the APD was calculated. Detection probabilities were calculated from this incident intensity and the measured number of APD detection events.

III. Results and Discussion

A. Dark Noise

Figure 5 summarizes the data for dark count frequencies for one RCA APD. Measurements were made at temperatures between 77 K and room temperature. As can be seen in these plots, the dark noise from the APDs increased more slowly with increasing bias voltage at intermediate temperatures 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 a bias voltage of more than 10 V above the breakdown voltage. Operating the detector at the highest possible bias voltage is desirable in order to obtain the greatest sensitivity.

The statistical frequency distribution of the lengths of the time intervals between noise counts was compared with a Poisson distribution using the chi-squared goodness-of-fit test. It was found that the dark noise counts were well-approximated by a Poisson process at very low (near 80 K) and high (near 300 K) temperatures. At intermediate temperatures (between 120 K and 200 K) the chi-squared test failed to show a good fit of the dark noise distribution to a Poisson distribution.

We interpret these results as being dependent on the dead time of the passive quenching circuit and may differ with the use of an active quenching circuit where dead times are approximately 10–20 ns. At high temperatures (> 200 K) the thermal carriers effectively dominate (due to the circuit dead time) while at lower temperatures the dominant noise is due to trapped carriers or secondary avalanches. Trapping of carriers occurs during an avalanche, presumably at imperfection sites in the semiconductor crystal lattice. Carriers trapped after a detection or noise event can remain in the lattice and dislodge, initiating a secondary avalanche, after a time ranging from nanoseconds to tens of minutes. Both the thermal generation of noise carriers and the release of trapped carriers are expected to be Poisson processes.

At high temperatures (i.e., near room temperature), since electrons are more mobile in the crystal lattice, trapped carriers are dislodged more quickly and most initiate secondary avalanches within the 6 μs dead time of the APD quenching circuit. Thus only a few avalanches due to trapped carriers are detected. At low temperatures (80 K to 120 K), trapped carriers remain trapped longer, and noise events due to them dominate those due to thermal carriers, whose numbers are greatly reduced at low temperatures.

At intermediate temperatures, detected events include a significant proportion of both the Poisson-distributed primary (thermal) events and the conditionally Poisson-distributed secondary (trapping) events. Thus the noise at intermediate temperatures does not fit a simple Poisson distribution.

B. Detection Probabilities

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. The intensity of incident light was determined from two independent measurements, one by the UDT photodiode power meter, the other by the PMT. From the intensity of the beam at each of these two points, using the measured transmission and reflection efficiencies of the two beamsplitters and the measured transmittance of the filters and other optics, the number of photons falling on the APD was calculated. Incident light intensities on the APD calculated from the photodiode data agreed within approximately 30% (or about 1/3 photon since we are detecting single photons) of that calculated from the PMT output data. As a further verification of the incident light intensity, a second PMT was used. The two PMT count rates were within approximately 25% agreement for similar incident light intensities of a few photons. This discrepancy reflects the uncertainties in the manufacturer's specifications for the quantum efficiencies of the PMTs. Despite this, we are reasonably confident that the light levels incident on the detectors are equal to or less than one photon per pulse for the experiment described here.

The output count frequency measurements of the "true," "false" and dark APD counts and the PMT output counts are summarized graphically in Fig. 6 for one RCA APD. Results have been scaled to represent a constant light intensity to both the PMT and APD. (Experimentally, approximately 1.7 times more light was incident on the PMT than on the APD.)

As can be seen in Fig. 6, dark counts remain less than 100 counts per second even with an over-bias of 10 volts (as described earlier). When light pulses are incident on the APD, more trapped carriers are generated. These carriers detrap causing a secondary avalanche after the primary avalanche has occurred. These secondary avalanches or false pulses increase the effective dark count rate. The rate of occurrence of these false counts is dependent on the over-bias of the APD. As the over-bias is increased, the false count rate also increases. It is expected that the false count rate is also a function of the light intensity incident on the APD. This will be further investigated at a later time. As can be seen in Fig. 6, the APD is still quite effective in spite of the generation of secondary avalanches since false count rates remain below 100 counts per second for an over-bias of about 1.5 volts on the APD. Even at this low over-bias, the APD true detection count rate exceeds the PMT count rate as shown in Fig. 6. As expected, the true count detection rate increases with over-bias voltage.

From this true count detection rate, a single-photon detection probability was calculated (as described above) for each voltage tested. Results are summarized in Fig. 7, and the appropriate false count levels are indicated. The uncertainty in this curve is approximately 30%, due mainly to uncertainties in the sensitivities of the PMTs. For a false count rate or effective dark count rate of 100 counts per second and an over-bias of about 1.5 volts, single-photon detection probabilities of approximately 27% were achieved. This is over twice that achievable with the C31034 PMT (quantum efficiency ~12% at 822 nm, cooled to 240 K). As can be seen from Fig. 7, single-photon detection probability approaches 50% for a 10 volt over-bias; however, the effective dark count rate nearly equals the signal count rate.

IV. Conclusion

Commercial avalanche photodiodes have been operated as single photon detectors by optimizing their operating temperatures and bias voltages. When operated under these conditions, the sensitivity of an APD can exceed that of a photomultiplier tube by more than a factor of two with less than 100 noise counts per second. At this sensitivity, the APD probability of detection was approximately 27 ± 8% at an over-bias of 1.5 volts. Thus APDs represent an attractive alternative to PMTs for applications in deep-space optical communications, as well as in other applications requiring sensitive, reliable, small or lightweight detectors, such as astronomy, remote sensing and fiberoptic communications.

References

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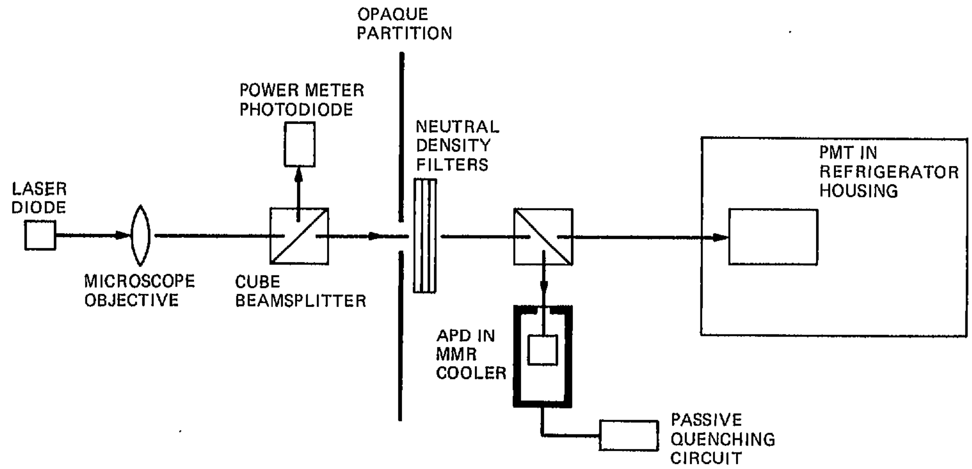

Fig. 1. Arrangement of optical components inside dark enclosure

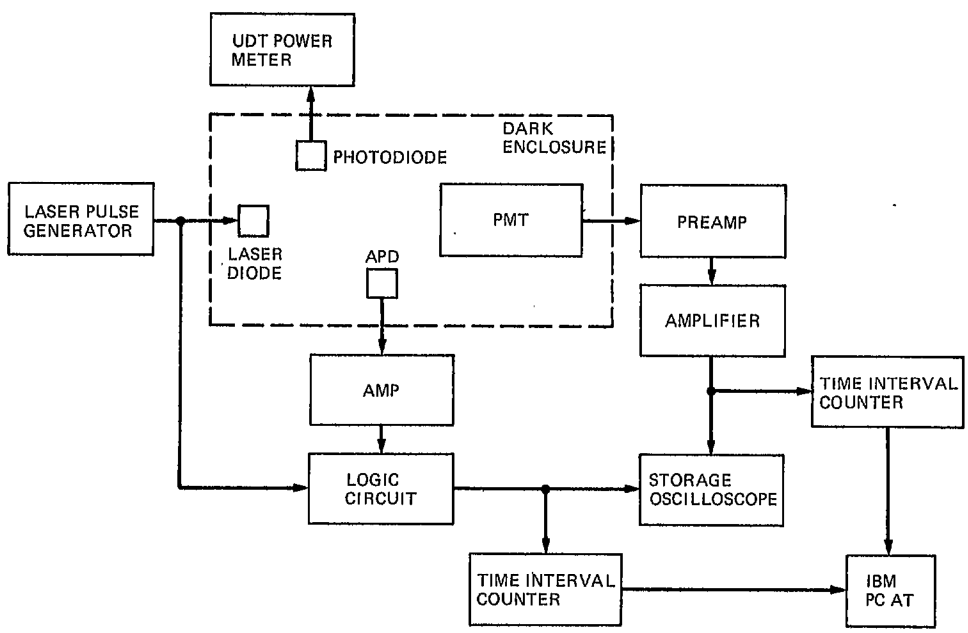

Fig. 2. Schematic representation of APD detection probability data acquisition and reduction apparatus. The amplifier for the APD output signal is necessary only for input to the TTL logic circuit. In general, further amplification of an APD signal pulse is not needed.

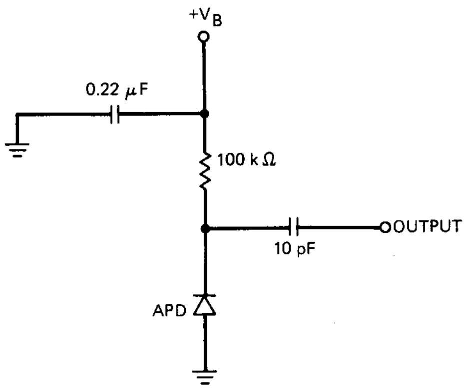

Fig. 3. Passive quenching circuit. Dead time of the detector using this circuit is about 6 μs.

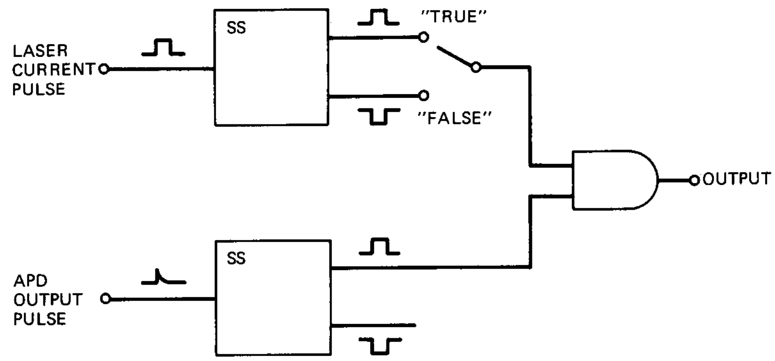

Fig. 4. Logic circuit for determining coincidence of APD output pulses with laser input pulses

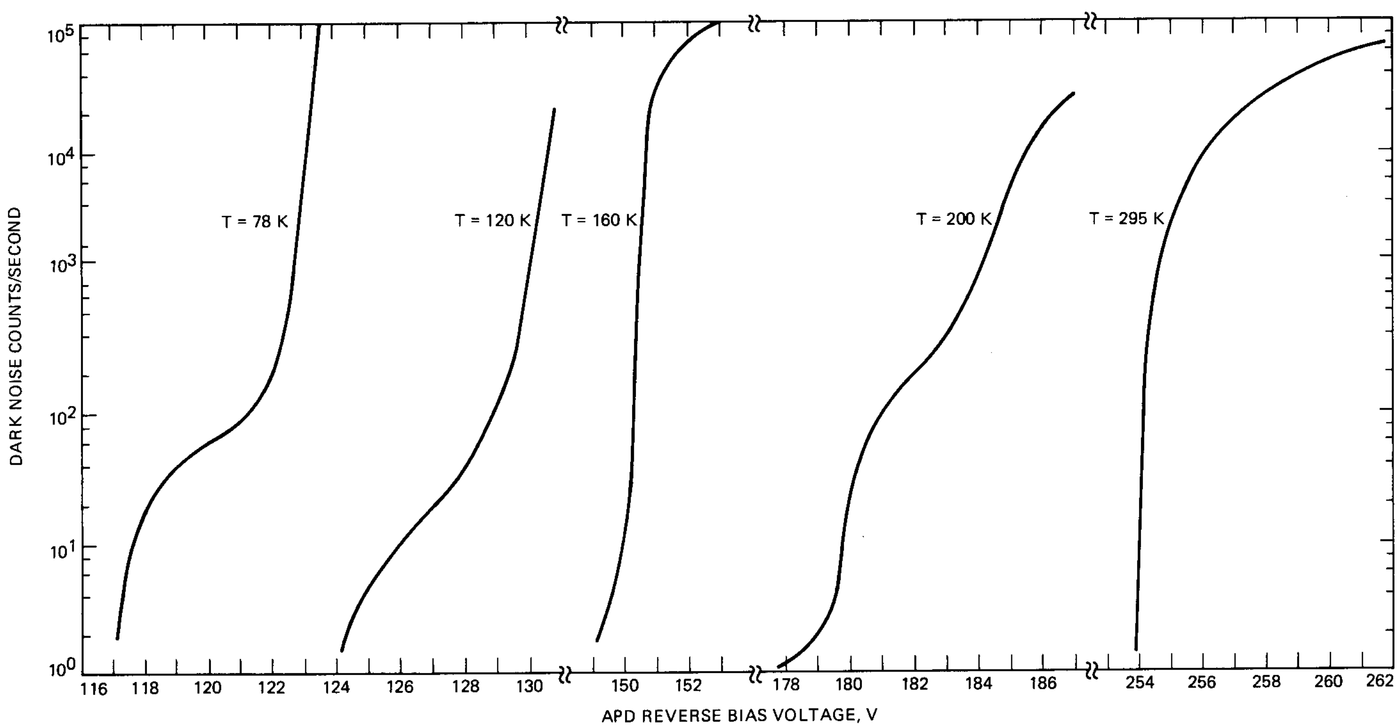

Fig. 5. Measured frequency of dark noise counts as a function of APD bias voltage and temperature (horizontal axis is discontinuous)

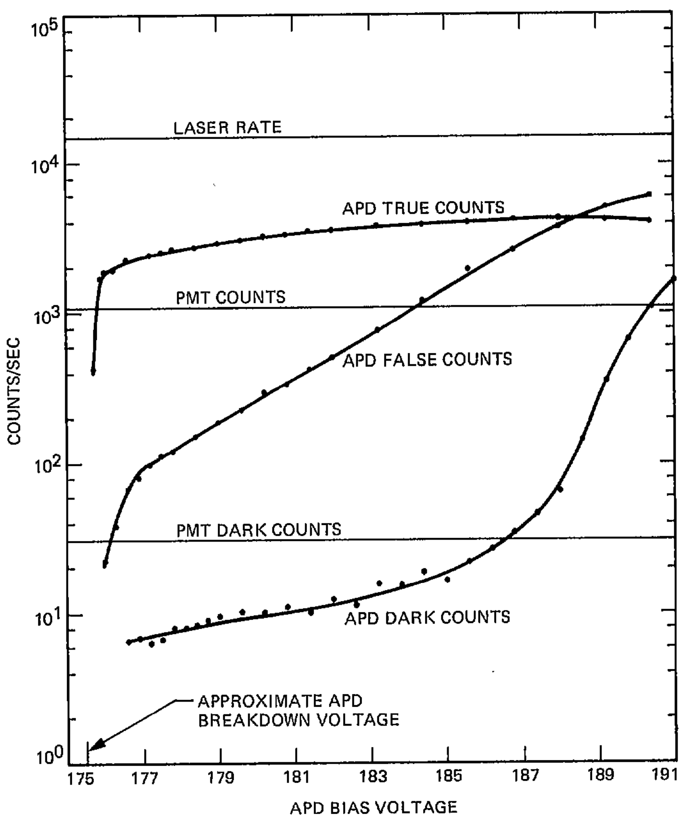

Fig. 6. APD output count frequencies as functions of bias voltage at 200 K for an RCA 30902S APD. Laser pulse rate was 15 kHz. The PMT (RCA 31034, quantum efficiency ~12%) count rate has been scaled to the same incident light intensity as the APD. APD breakdown voltage was approximately 175.5 V at 200 K.

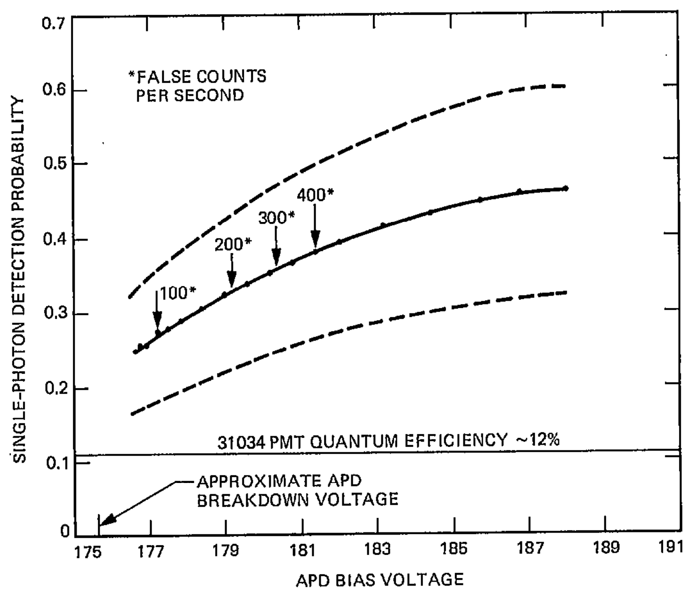

Fig. 7. APD single-photon detection probability as a function of bias voltage at 200 K. Effective dark ("false") count rates are indicated. Uncertainty (dashed curves) in this curve is estimated to be 30%.