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Design and Testing of an Active Quenching Circuit for an Avalanche Photodiode Photon Detector

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The photon-detection capabilities of avalanche photodiodes (APDs) operating above their theoretical breakdown voltages are described, with particular attention given to the needs for and methods of quenching an avalanche once breakdown has occurred. A brief background on the motives of and previous work with this mode of operation is presented. Finally, a description of the design and testing of an active quenching circuit is given. Although the active quenching circuit did not perform as expected, knowledge was gained as to the signal amplitudes necessary for quenching and the need for a better model for the above-breakdown circuit characteristics of the Geiger-mode APD.

I. Introduction

For deep-space optical communications, received data signals will consist of a few photons per bit of received information. One of the enabling technologies for the implementation of optical communications in the deep-space environment is the development of detectors with sufficient sensitivity and gain to operate in a single-photon detection mode. To a degree, conventional photomultiplier tubes (PMTs) are suitable for this purpose, when they are used in ground-based receivers. The signal gain for photomultiplier tubes can be 10^8 for the spectral region of interest (0.5–1.1 μm). But in this range, the quantum efficiency of conventional photomultiplier tubes is limited to ~2 percent at 0.5 μm and less than 1 percent at 1 μm. Out of a need for higher quantum efficiency, high-gain optical detectors, the JPL Optical Communications Group in 1984 began to seek out alternative detectors. This work was undertaken to develop optical-wavelength detectors that would be suitable for use in DSN-type communications applications.

Avalanche photodiodes (APDs) are photosensitive diodes that are operated under a large reverse bias. Incident photons that cause ionization (the creation of hole-electron pairs) within the diode's depletion region, as well as thermally generated carriers, can, with a certain probability, under the influence of a high electric field (~3×10^5 V/cm), start a chain reaction of ionizing collisions that result in the diode breaking down, or avalanching, and conducting current. Additionally, charge carriers trapped within the depletion region during a previous avalanche can also "detrap" and cause another avalanche. In any event, if the reverse bias is less than the breakdown voltage, such a chain reaction is not self-sustaining, and the APD quickly reassumes its nonconducting state until the next ionizing event causes another avalanche. As the reverse bias is increased, both the probability of an ionizing event causing an avalanche and the amount of current resulting from the avalanche, i.e., the gain, increase.

In the early 1980s, researchers at RCA–Canada began experimenting with operating APDs beyond their breakdown voltage to realize photon detectors with signal gains comparable to those of photomultiplier tubes, but with the higher quantum efficiencies associated with APDs [1,2].

If an APD is biased beyond its reverse breakdown voltage, it will suffer avalanche breakdown and begin to conduct current. Unless the current is limited by external circuitry, the breakdown current will increase and destroy the diode. But it is important to note that breakdown results from free minority carriers transiting the diode's depletion region. If such carriers are made unavailable, breakdown cannot be spontaneously initiated, even if the bias is above the nominal breakdown voltage. In fact, the availability of free carriers can be greatly reduced by cooling the diode. For example, RCA-type C30902 silicon APDs can be operated at ~6 V over breakdown, producing $\leq$10 dark counts (avalanches) per sec when cooled to 200 K [3]. An avalanche can now be triggered as a result of a single incident photon generating a hole-electron pair in the depletion region. Such an avalanche, which has a probability of ~0.4 of occurring under the above conditions, can achieve a current gain of 10^8 to 10^9. As a result, when used in this mode, a single photon can be detected with conventional amplifying techniques. This yields a solid-state detector whose gain is comparable to that of a PMT, but whose photon detection probability is 3–4 times higher. This mode of overbiased operation is referred to as the Geiger mode. The rate at which incident photons can be counted depends on how quickly the external circuitry, preparing the APD for the next photon event, can detect and quench the avalanche.

Deep-space optical communications will likely implement pulse position modulation (PPM) data transmission formats. An optical PPM format requires distinguishing a particular time slot that contains a few signal photons plus some noise photons from a time slot with only noise photons. Increasing the signal-to-noise ratio is achieved by shortening the slot times, thus reducing the number of noise photons per slot. But using currently available lasers and modulators, PPM slot times of 10 nsec are realizable. Implementing this technology requires detectors capable of timing resolutions of a few nanoseconds. Beginning in 1984, the Optical Communications Group at JPL worked on using APDs in the Geiger-mode as high-gain, high-quantum-efficiency optical communication detectors [3–5]. Initially, the APD avalanche was detected and quenched by using the passive network shown in Fig. 1. This circuit was capable of quenching the APD in ~6 μsec [4]. Clearly, quenching times of at least three orders of magnitude shorter than those obtainable with the passive quenching circuit are necessary in order to implement PPM with time slots on the order of 10 nsec. C.-C. Chen has shown that receiver error rates degrade rapidly with increasing dead times [6]. Figure 2 shows the transmitted power penalty incurred by a communications system as a function of the detector dead-time when used in a binary PPM system. It can be seen in Fig. 2 that the power penalty incurred to hold to a particular probability of a bit error (PBE) begins to grow rapidly when the detector dead time exceeds one tenth of the PPM slot width (T_s). Quenching circuits that use high-speed active elements have been developed by several groups [7–9], with 20–30-MHz operation being reported. An evaluation of available electronics indicated that 10-nsec quenching times were feasible. Given this, requirements were gathered for an active quenching circuit with a 10-nsec recovery time capable of operating an APD in the Geiger mode up to 5 V over breakdown.

II. Active Quenching Circuit for Geiger-Mode APD

An active circuit was designed as a joint effort of the Optical Communications Group in the Communications Systems Research Section and the New Products Development Group in the Radio Frequency and Microwave Subsystems Section. A schematic of the design is shown in Fig. 3. The design employs high-speed GaAs components. The purpose of the circuit is to detect and quench an avalanche as quickly as possible, thus minimizing the detector's dead time and maximizing the photon count rate. The assumptions used in the design were that the overbias range would be 3–5 V and that the quenching pulse should pull the APD bias just below the breakdown voltage. A replaceable delay line was used to add flexibility in establishing the optimal length of the quenching pulse.

A small bias voltage VN is applied to one end of the resistor $R1$. This voltage determines the steady-state output voltage of the transimpedance amplifier $U1$. The other end of $R1$ is the crucial node in the circuit that connects to the cathode of the APD and to the output of the quenching pulse switch. When the −4.5-V quenching pulse is applied, the Schottky barrier diode $Z1$ isolates this node from the input of the transimpedance amplifier. The APD, $D1$, is biased beyond breakdown (−175 V at 200 K) by applying a negative voltage to the anode. At steady state, the diode is an open circuit. At the onset of an avalanche, the diode begins to conduct current, which is subtracted from the (internal) feedback resistor of $U1$ and which causes the output voltage to decrease in amplitude (but increase in absolute value, since it is negative). The output of the transimpedance amplifier is connected to the negative input of the comparator, $U2$, through $R2$. The positive input of $U2$ is connected through $R3$ to a variable voltage reference, which is set 30–100 mV above the nominal value of the negative input. $R2$ and $R3$ help reduce oscillations of the comparator that result from the fact that the two inputs have similar values. The comparator has two outputs: an inverted output used to monitor the state of the circuit (pulse out) and a direct output which goes low when an avalanche is detected, and which stays low while the quenching pulse is applied to the APD. The negative edge of the comparator output clocks a flip-flop, $U4$, applying "ON" voltages to the switch, $U5$, which applies the quenching pulse. The comparator output, delayed by a fixed 20-nsec delay line, $U3$, presets the flip-flop, which turns off the switch and ends the quenching pulse. The Zener diodes, $Z2$ and $Z3$, are used to offset the logic level, as required for the switch control signals. When the quenching pulse ends, steady state is resumed, the comparator output goes high, and the circuit is ready to detect another avalanche.

III. Test Results

The active quenching circuit was tested in stages in order to effectively assess its performance separately from the effects of the avalanche diode. Results indicate that the temporal characteristics of the diode are different from the assumptions used in the quenching circuit design. First, the avalanche current does not increase quickly and smoothly. It takes a few nanoseconds rather than subnanoseconds to build up, and the current may not build monotonically. This was deduced by observing the circuit's output characteristics since the diode current could not be observed directly without affecting its response. In addition, for the Geiger mode of operation, a 3–5-V quenching pulse appears to be insufficient for terminating the triggered avalanche current. The above results indicate that new requirements are needed for a future active quenching circuit design. The following is a more detailed description of the tests and measurements conducted on the active quenching circuit.

A. Initial Circuit Characterization

The active quenching circuit was first assembled in an open-loop configuration to test the signal-propagation delay and rise time. $U2$ and $U4$ were disconnected from each other, and $D1$ was left out. $U4$ was driven by an external clock from a signal generator. The delay and the pulse rise time at the output of the switch were measured with the following results: (1) The delay from comparator output to the switch output was 2.4 nsec and (2) the quenching pulse rise time (to 90 percent of peak value) measured without $D1$ was 6 nsec, and with $D1$, it was 10 nsec. The rise time with $D1$ is longer because the comparator input must return to within a few tens of millivolts of its steady-state value. The capacitive reactance of $D1$ effectively slows the return of the comparator input to its nominal value.

Next, the loop was closed (again without $D1$), and a small signal square wave was superimposed on VN to simulate avalanche events. When the circuit proved to work as a closed loop, i.e., the pulses superimposed at VN caused quenching pulses to be generated at $U5$, it was connected properly, as shown in Fig. 3, with $D1$ included and activated. Output pulse widths measured at the inverted output of $U2$ were quite long—100 nsec for a fixed delay line of 20 nsec (see Fig. 4). That is, the circuit took 80 nsec to respond to the reset signal, an order of magnitude slower than with the APD absent.

As can be seen in Fig. 4, there was a delay of approximately 80 nsec from the rising edge of the quenching pulse (upper trace) to the falling edge of pulse out (lower trace). This was the circuit reset time with the APD present.

When the oscilloscope was triggered on the falling edge of pulse out, a quenching pulse immediately preceding it was observed. Figure 5 shows pulse out, the lower trace, and the quenching pulse at the control input of $U5$, the upper trace. This suggests that a second, later quenching pulse is required to actually reset $D1$, although the occurrence of this later quenching pulse would be the result of noise.

B. Test Configuration 1

In order to characterize the circuit response time, the quenching circuit was connected as shown in Fig. 6. A signal was injected into a spare comparator, using it to generate fast-rising square waves to clock the flip-flop. The flip-flop generated quenching pulses that caused the circuit comparator to change output states. The APD was connected to the quenching node, but it was biased below breakdown so that no self-sustaining avalanches occurred. This test enabled the authors to measure the time required for the comparator to respond to the drop in current (simulating an avalanche event), as well as the time required to restore the circuit to its quiescent state following the end of the quenching pulse.

Figure 7 shows the comparator's negative input (top) and its output, pulse out (bottom). Since the negative input falls gradually, adjusting the reference voltage (at the input of $U2$) will time-shift the inputs' crossover point and, hence, affect the width of the output pulse. By raising this threshold voltage, the comparator's output pulse width can be decreased to 10 nsec. The increase in the threshold would mean that the diode current will rise to a higher value before an avalanche is detected. If the threshold is increased, the circuit response time is but a few nanoseconds (even with the APD attached and biased below breakdown). Yet, in normal overbiased operation, pulse widths are much longer. This implies that the APD is not capable of being quenched within the quenching pulse width possibly because the quenching pulse is not of sufficient amplitude to take the APD far enough below breakdown to quench an avalanche. Unfortunately, the use of the GaAs circuitry, which enabled the generation of short propagation-delay signals, restricts pulse amplitudes to 4–5 V.

Figure 8 shows the quenching pulse when the switch is driving only the 500-ohm oscilloscope probe. Under this condition, the switch is able to provide a clean, sharp transition. In the circuit, however, the switch is driving a capacitive load (the APD). The top trace of Fig. 9 shows that the quenching pulse when driving the APD is neither sharp, deep, nor smooth, which implies that the APD may not be quenched by any given quenching pulse. The bottom trace of Fig. 9 records the pulse out produced by the quenching circuit when driving the APD.

C. Test Configuration 2

Test Configuration 2 was a modification of the original circuit, designed to clarify the following problem observed in Test Configuration 1: The GaAs comparator requires a subnanosecond monotonically rising edge, or it will oscillate. The comparator responded to subnanosecond test signals without oscillations. Yet, when the APD avalanched, the observed oscillations suggest that the APD's current increase is relatively slow and possibly jittery as well. The recharging of the APD plus the comparator response time contributed about 12 nsec to the total circuit reset time as observed at pulse out. The GaAs single-pole single-throw switch, a Gigabit Logic S0030, has 0.5-nsec switching time for a 4.5-V pulse when properly terminated with 50 ohms. In the original circuit, however, the switch is terminated in the quenching node, which consists of the APD, another diode, and a resistor. This impedance mismatch slows down the pulse response.

Test Configuration 2 is shown in Fig. 10. The switch, the transimpedance amplifier, and the Schottky barrier diode were eliminated. The quenching pulse was reduced to an amplitude of 2 V, by using proper termination. There was less amplification of avalanche current so the comparator operated close to the threshold.

As can be seen from Fig. 11, pulses of about 40-nsec duration can be obtained on pulse out (lower trace). The 20-nsec quenching pulse (upper trace) appears square at the flip-flop output. However, the comparator shows 500-MHz oscillations around the rising edge.

IV. Summary

A high-speed circuit to quench avalanche breakdowns resulting from photons incident upon an avalanche photodiode has been designed, fabricated, and tested. The active quenching circuit takes 2.4 nsec following the detection of an avalanche breakdown of the Geiger-mode APD to initiate a quenching pulse. Approximately 12 nsec are required for the APD to recharge and for the comparator to reset following termination of a quenching pulse. In order to minimize response time, the circuit was designed for a maximum quenching pulse amplitude of 4.5 V, which proved insufficient for reliably quenching actual avalanches. Pulse amplitudes of 10–25 V have been used by other groups [7]. Testing showed that the active quenching circuit would eventually quench and reset the over-biased APD after approximately 80 nsec, but that the quenching probably resulted from noise. Future development of active quenching circuits will involve different requirements, such as larger quenching pulses at a matched impedance node and a subnanosecond, highly sensitive comparator.

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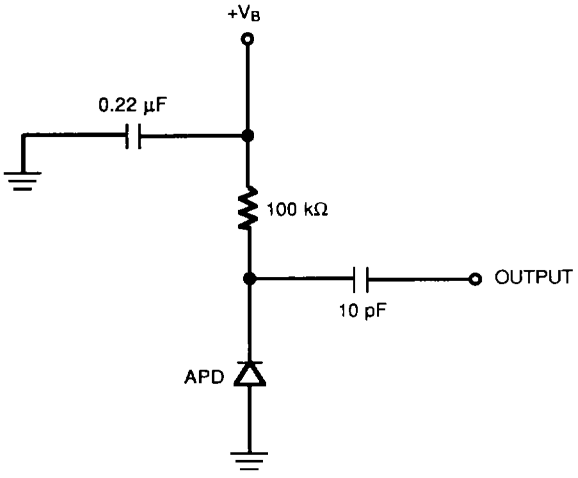

Fig. 1. Passive quenching circuit. Dead time of the avalanche photodiodes using this circuit is 6 µsec.

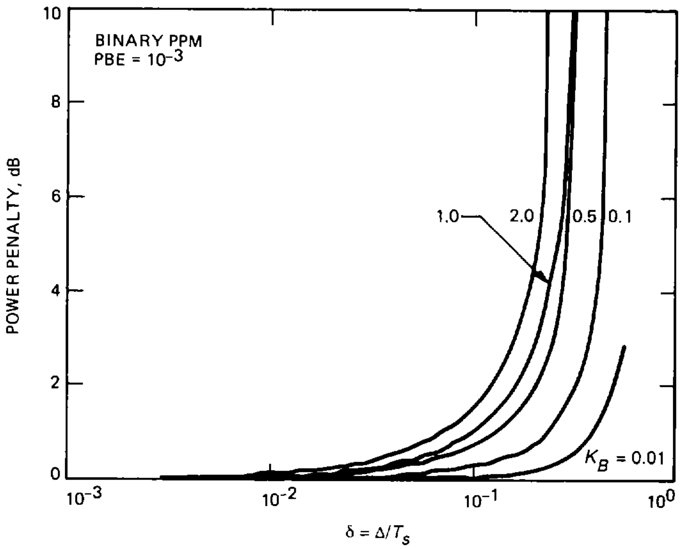

Fig. 2. Power penalty due to detector dead time for a binary pulse position modulation receiver at different background intensities.

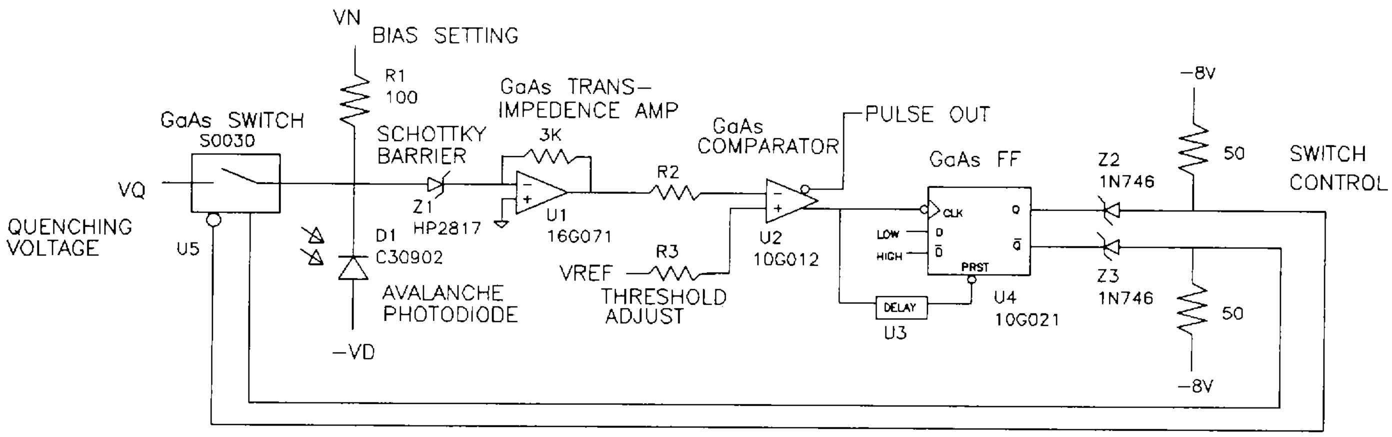

Fig. 3. Active quenching circuit for avalanche photodiodes using GaAs technology.

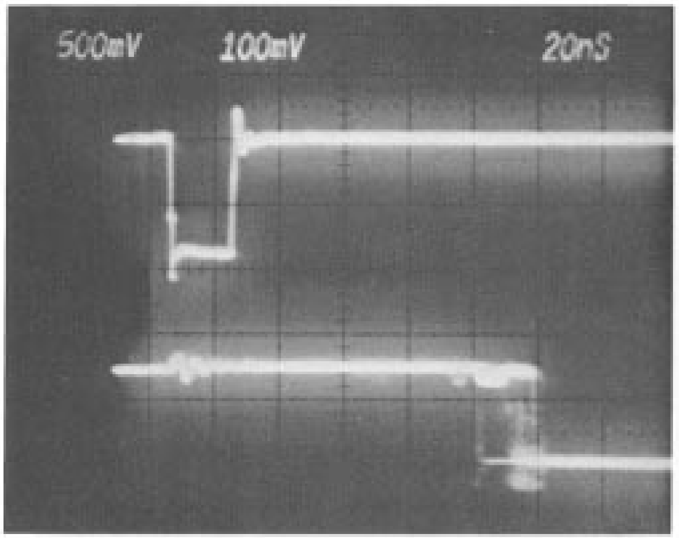

Fig. 4. Triggering the scope on the rising edge of the quenching pulse control signal (upper trace) shows the delay to pulse out reset (lower trace) is 80 nsec.

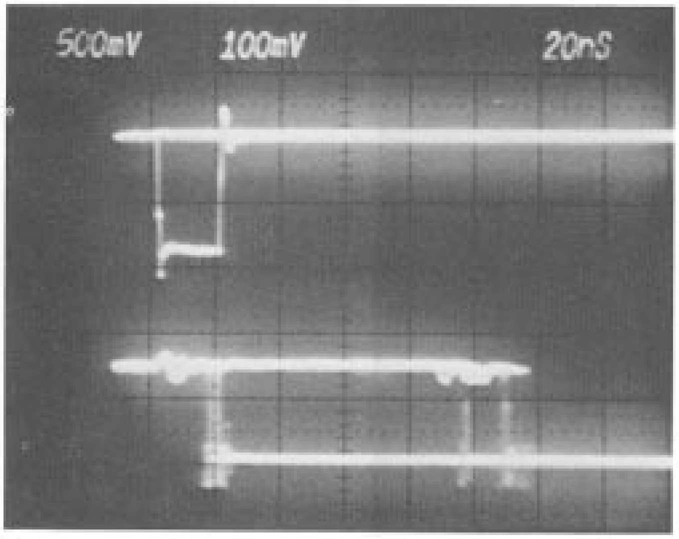

Fig. 5. Triggering the scope on the falling edge of pulse out (bottom trace) shows that a quenching pulse preceded it (upper trace).

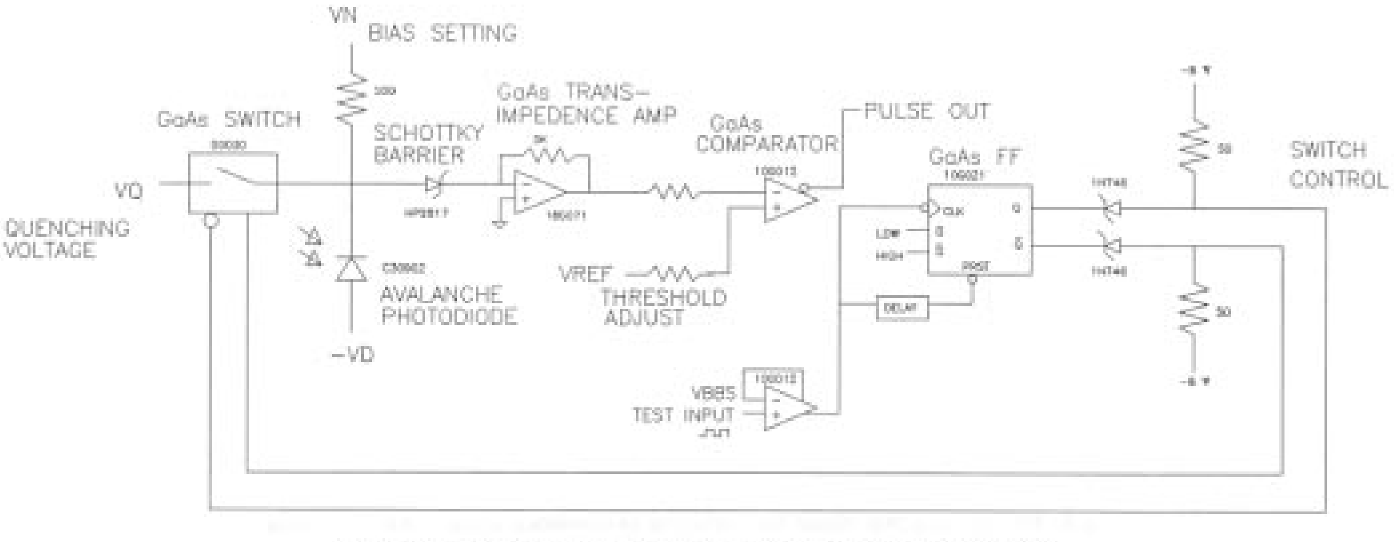

Fig. 6. Test configuration: quenching pulses occur, but no avalanche.

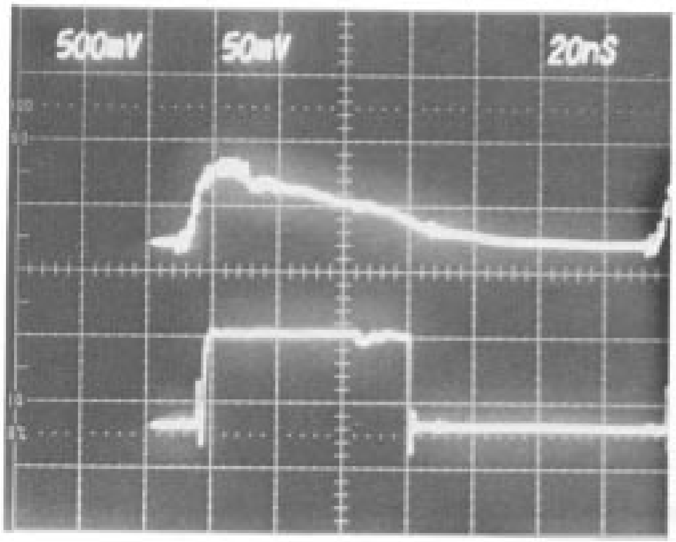

Fig. 7. Comparator input (top trace) versus output (bottom trace) shows that pulse width depends on the threshold.

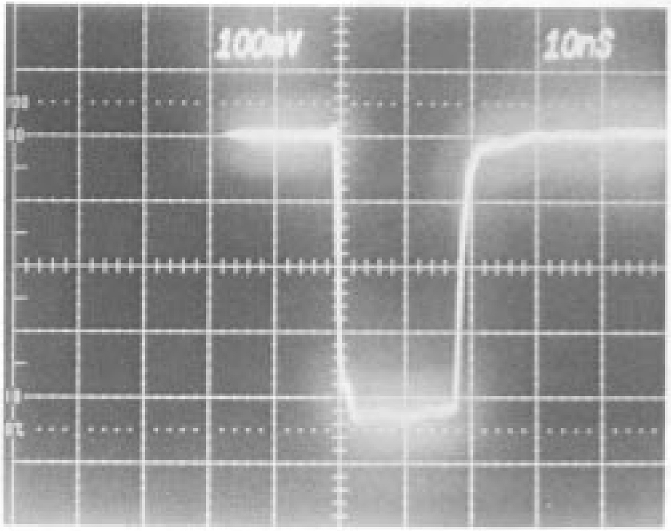

Fig. 8. Quenching pulse, *RL* = 500 ohms.

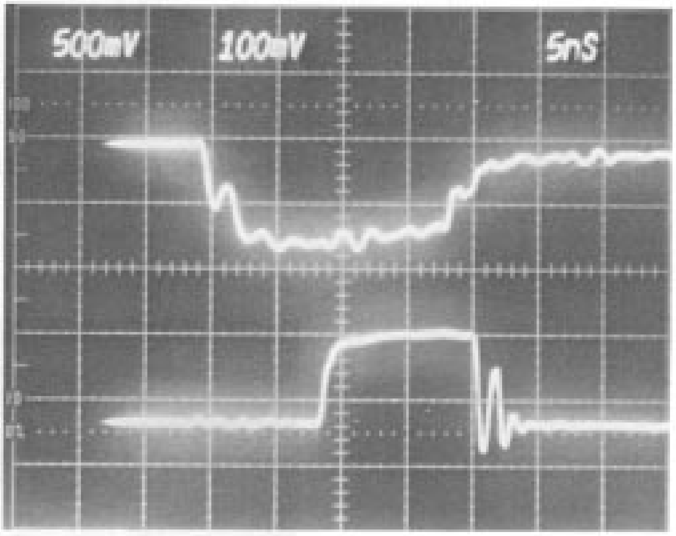

Fig. 9. Top trace: quenching pulse driving the APD; bottom trace: pulse out.

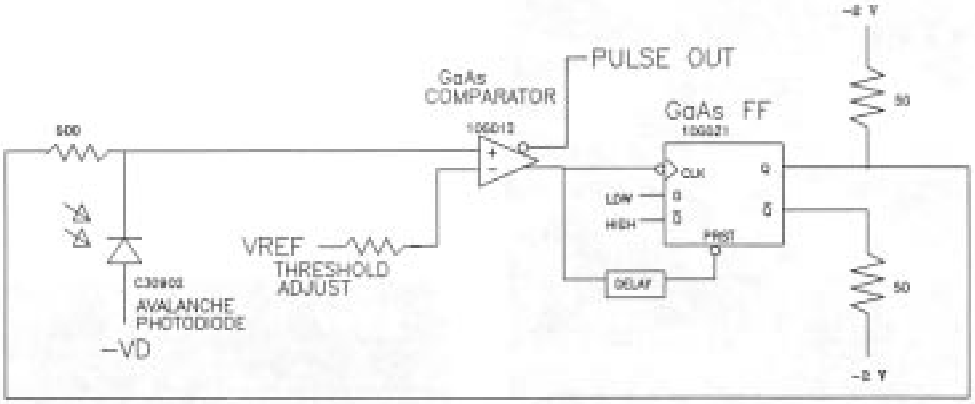

Fig. 10. Test configuration: eliminating switch, transimpedance amplifier, and Schottky diode.

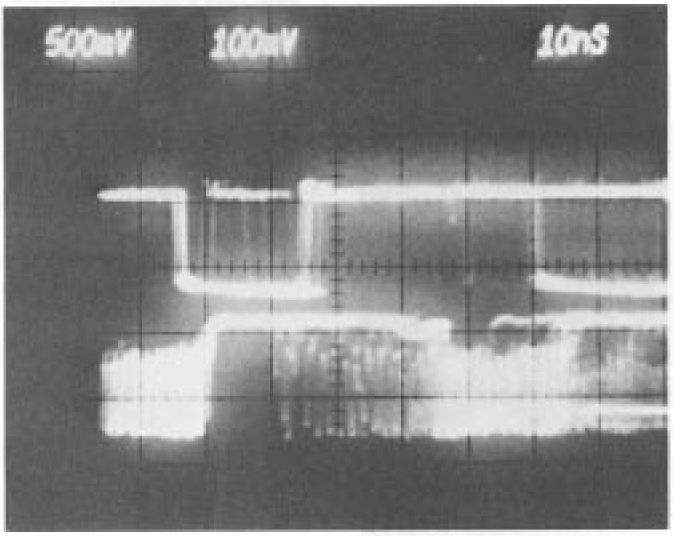

Fig. 11. Top trace: quenching pulse, 20 nsec; bottom trace: pulse out, 40 nsec.