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A microcontroller-based failsafe for single photon counting modules

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Avalanche photodiode-based single photon counting modules (SPCMs) can be damaged by exposure to excessive light levels. A flexible and inexpensive failsafe is presented which has been shown to protect SPCMs from light levels far exceeding the damage threshold. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1531825]

Avalanche photodiodes have higher quantum efficiency and other significant advantages over photomultiplier tubes for photon counting with very low light levels and have become the standard detector in a wide array of fields ranging from single-molecule fluorescence to quantum optics. However, they have some notable disadvantages, such as cost, availability, and perhaps most vexing, extreme sensitivity to excessive light levels. Perkin-Elmer manufactures a popular avalanche photodiode (APD)-based single photon counting module, the SPCM-AQR. They note that above 5 million counts per second (5 Mc/s) performance is degraded due to self-heating of the photodiode.[1] Average room lighting can easily exceed 10 Mc/s, and experience has shown that exposure to this level of light for greater than a few milliseconds leads to catastrophic failure of the single photon counting module (SPCM), requiring it to be replaced. We set out to design a simple and inexpensive circuit to protect SPCMs from damage due to excessive exposure. Our criteria were as follows.

1. The failsafe must detect damaging conditions and take corrective action at least an order of magnitude faster than the observed failure time ($\sim$10 ms).
2. The likelihood of detecting a false-positive must be very low.
3. The failsafe must always be active whenever the detector is on.
4. It must be inexpensive and simple to construct.

Based on the first criterion, we imposed an upper limit of 100 μs on the detection and shutoff time for the failsafe. We also chose to use the SPCM's internal "gate" input as the mechanism for shutting down the device, since shuttering the excitation source—in our case, a laser—takes on the order of 50 ms and would not protect against exposure to room lights. Bringing the gate input low suppresses photon detection in the SPCM with very high efficiency and has been used in our lab to protect the SPCM from the intense light levels used in photobleaching experiments.

Based on the second criterion, we chose to use the SPCM's own digital photon counting output as the detection mechanism, since it would be the most direct measure of the SPCM's light exposure. The third criterion led us to design a solid-state, self-enclosed device which could be left on at all times with low power consumption, and the fourth made us choose a microcontroller-based system that would be cheap, easy to configure, and flexible. A flowchart of the program[2] for the microcontroller is shown in Fig. 1, and the hardware is shown in Fig. 2.

The basic mechanism implemented by the failsafe circuit is that if the SPCM counts more than a certain number of photons in 10 μs in two consecutive 10 μs periods, it brings the SPCM gate input low, protecting the SPCM from damage. The circuit is based on the RCM2000 RabbitCore microcontroller, available from Rabbit Semiconductor. The RCM2000 is relatively inexpensive (the development kit costs approximately $170, but individual microcontroller units can be purchased for approximately $70), and can be programmed in C using the RabbitCore Dynamic C compiler, making it very simple to configure and use. However, since the RCM2000 is not fast enough to count pulses at megahertz rates, the failsafe uses an external counter, the LS590. The LS590 is an ideal choice because it has a single 8-bit counter and a built-in 8-bit storage register, enabling the count value to be transferred to the register and the counter cleared and ready for the next counting cycle while the register is being read out.

The microcontroller starts by pulsing high bit zero of parallel port A (PA0 in Fig. 2). This transfers the current value in the 590 counter into the register, and clears the counter. Next, it reads the value in the register into parallel port E, and compares it to the threshold value. In our device, the threshold is set to 10 photons, corresponding to 1 Mc/s. This value can be changed, if desired, by simply reprogramming the controller. As noted above, the failsafe is only tripped if the threshold has been exceeded twice in a row. (For efficiency, in the actual software this is achieved by clocking and checking the counter twice in a row, rather than looping over the clock-check cycle.) The reason for the double check is that the SPCM-AQR has a large amount of

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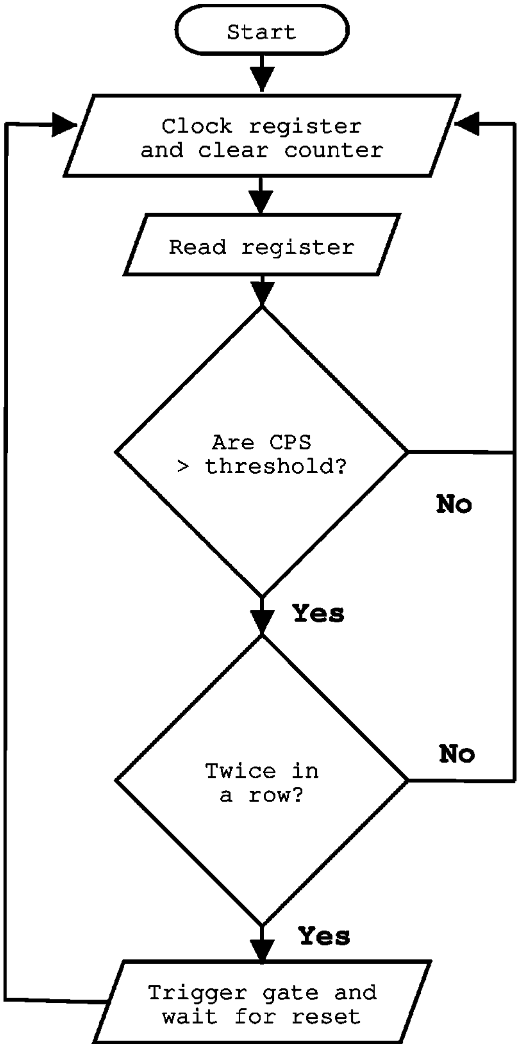

FIG. 1. A flowchart representing the microcontroller program.

"gating noise," in the form of nonphoton-induced digital pulses which occur less than 2 μs after the application of the gate signal. For our application, gating the detector is necessary, and without the twice-in-a-row check, gating the detector would cause the failsafe to trip immediately. By checking that the threshold has been exceeded twice in a row, a single instance of gating noise will not trip the failsafe. If the threshold has been exceeded twice in a row, the microcontroller brings PA1 low, and waits for PB2 to go high, indicating that the reset switch has been pressed. After being reset, the microcontroller returns to the top of the loop and restarts the cycle.

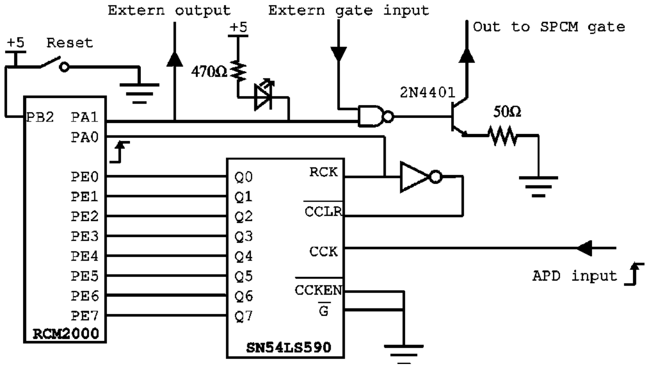

FIG. 2. A microcontroller-based SPCM failsafe.

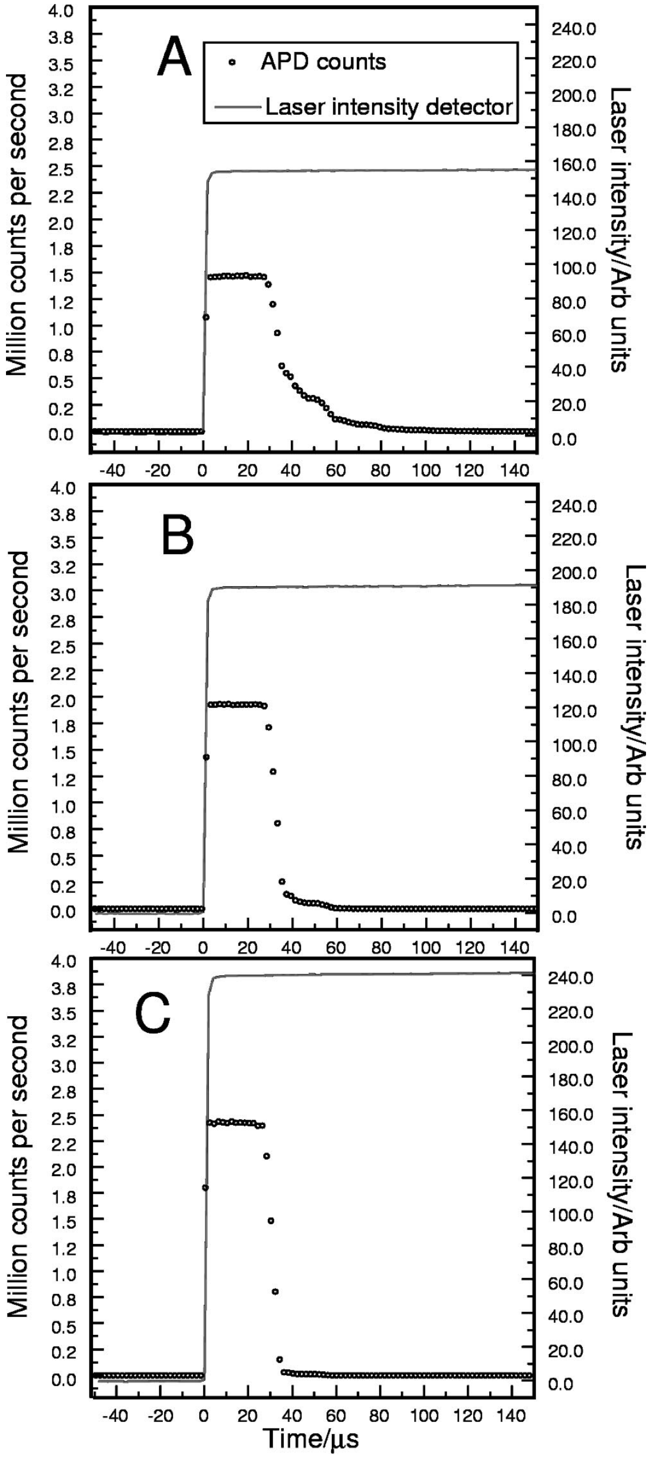

FIG. 3. Test of the APD failsafe at three different laser intensities above the shutoff threshold. The solid line shows the laser intensity (scale on the right side of the figures) and the dots indicate the counts per second from the APD (scale on the left side). Each figure represents cumulative results of 50 000 trials.

In our design, the PA1 line does not directly control the SPCM gate. Instead, PA1 inputs into a NOR gate, along with an external input. This allows us to maintain external control of the gate circuit without disconnecting the failsafe. If either

PA1 or the external gate control go low, the NOR output goes high. The NOR output in turn controls a simple single-transistor current sink. The gate input of the Perkin-Elmer SPCM-AQR sources a relatively large current, from 40 to 90 mA, varying from unit to unit. It is necessary to sink this current in order to bring the gate low, hence the need for the current sink. Bringing PA1 low also lights the LED, giving an immediate visual indication that the failsafe has been tripped, and it also brings the external output low. In our experiment, the main control software monitors the status of the failsafe external output, and halts the experiment with an appropriate warning if the failsafe is tripped.

We tested the time response of the failsafe by focusing a laser into a confocal microscope and onto a fluorescent sample. The emitted light was collected, filtered to remove the excitation light, and focused onto the SPCM detector. The laser intensity was measured using a high speed photodetector (ThorLabs). Test results are shown in Fig. 3. Three different intensities are shown at differing levels above the failsafe threshold, which was set at 1 Mc/s. At values close to the threshold [Fig. 3(a)], the APD is shut off within 30 μs of overexposure approximately 65% of the time, and is shut off essentially 100% of the time within 100 μs of overexposure. These results, as well as the inflection in the curve at the 30 μs point, are consistent with the shutoff delay being governed by Poisson statistics of the emitted light. Even the longest shutoff time at this intensity level is two orders of magnitude faster than the observed failure time cited above. Further, as Figs. 3(b) and 3(c) show, at higher intensities, the shutoff becomes much quicker, again because of Poisson statistics: at higher count rates, the likelihood of the count rate being above the threshold for two consecutive bins approaches 100%. At 2.4 Mc/s [Fig. 3(c)], the likelihood is effectively 100%, and shutoff is always complete within 40 μs.

In summary, we have demonstrated that a cost-effective, relatively simple failsafe circuit can be constructed from off-the-shelf parts which will consistently protect APD-based SPCMs from damage due to overexposure. Though we did not collect statistics on such cases, this circuit has protected APDs in our lab from exposure to tens of millions of counts per second for several minutes continuously, as well as routinely protecting it from minor overexposure levels.

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[1] *Single Photon Counting Module SPCM-AQR Series Datasheet* (Perkin-Elmer Optoelectronics, Fremont, CA, 2001).

[2] Source code is available at http://www.physics.uiuc.edu/People/Faculty/Selvin/PSCV.html#Publications