Novel avalanche photodiode for adaptive optics

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ABSTRACT

We report about the development of novel circuitry for solid state photon counting devices, based on avalanche photodiodes (PC-APD), and tailored for adaptive optics applications. The recent development of EG&G SlikM devices, has improved silicon APDs considerably, reducing the afterpulsing effects, improving the effective Q.E., and reducing the dark current to negligible values. These new APDs allow to conceive new quenching circuitry and new applications of solid state photon counters for improved adaptive optics performance.

Although EG&G has currently commercially available PC-APDs, they are not optimized for adaptive optics use. We have built and tested around the new SlikM devices new circuitry. The goal is to develop quad-cell units composed of a hybrid with the APD quenching circuitry, quad cell modular electronics with N/S and E/W unbalance signal outputs, and a controller for the quad-cell modules. These units could serve as an optimized star tracker, or else as base of the detector for the Shack-Hartmann wavefront sensor subapertures. The applications in mind of the authors is for a laser guide star based adaptive optics servo-system for astronomical use, operating at near infrared wavelengths and shorter, such as in the LBT telescope project foreseen Adaptive Optics implementation.

1. Novel Avalanche Photodiodes

This work is based on a novel type of super-low-k APD (SlikM) from EG&G¹, which is not yet commercially available, and it has been provided to us under courtesy of EG&G. This device is likely to substitute in future years the well tested C30921S and C30902S APDs from EG&G, used in photon counting modules of the SPCM series, such as those used by the CFHT HRCam, the UoH curvature sensor, and the SOR-Phyllips lab group. These commercial photon counting modules do not reach an effective quantum efficiency higher than 55% at 0.632 µm, and have a passive quenching circuitry with maximum cycle period of 500 nsec, i.e. can not discriminate between photons arriving within this period of time. To lower the dark current they are kept below -20 °C, and come mounted in a module with a Peltier cooler. When applied at the focal plane of a telescope the generated heat has to be removed by means of forced ventilation in a pressure tight chamber or other heat extraction mechanisms.

However quantum efficiencies in excess of 85% have been measured¹ at 500 nm with the new Slik-APDs. Taking advantage from the previous experience on active quenching circuitry,² our group has collaborated toward the production of a circuit which allows to discriminate between photons arriving within 40 nsec of time, quenching the avalanche effect within 20 nsec, thus minimizing the afterpulsing and the light emission effects intrinsic to the APD operation in Geiger mode. If a quad-cell of this type can be produced, the operational advantages and goals are as follows:

a) with respect to the limiting magnitude of the tracking natural guide star (NGS), compete successfully with low noise, fast read-out CCDs for star tracking, thanks to the zero read-out noise;

b) compete successfully with fast read-out CCDs, when used in a Shack-Hartmann sensor, thanks both to the zero noise (which reduces the laser guide star or the NGS power required) and to the parallel read-out advantage. In particular the latter allows two significant advantages in the servo system, which become substantial for operation at high servo-loop frequencies:
i) a fast readout CCD takes usually a certain integration time + 1 msec for readout (for a 64x64 frame), which introduces a net phase delay in the servo-loop transfer function;  
ii) the parallel readout of each diode allows to perform real time summing and normalizing operations, simulating the behavior of conventional analog quad-cell photodiodes and hence eliminating again the net phase delay term in the servo-loop transfer function due to detector integration time. This advantage should not be underestimated and it is illustrated quantitatively below;  
c) allow electronic range gating, with nsec precision, which eliminates current rotating wheels solutions and moving parts in front of the wavefront sensor for Rayleigh backscatter sensing. The upgoing laser beam is encompassing 1 Km in 3.3 \microsec, hence a 33 nsec discrimination between counts would allow 100 counts/Km-pxl. This can allow multiple range sensing as well, aiming at atmosphere tomography for multiconjugate adaptive optics wavefront sensing.

2. Tracking error gains

Let us assume that a 16x16 adaptive servo system is operating on a 3.5m diameter telescope, such as the italian Galileo national telescope (TNG), under 0.7'' seeing at 0.55 \mu m and 10 m/s wind speed. Assume that the system is correcting wavefront aberrations above tip-tilt (high orders) with a NGS, and a wavefront variance residual of 1.12 rad\(^2\) and 0.54 rad\(^2\), at 0.7 \mu m (R-band) and 2.2 \mu m (K-band) science imaging, respectively. The tip-tilt servo-loop has a separate tracking sensor, based on a 4-pixel, quad-cell scheme. We compare now the sensor performances in terms of Strehl Ratio induced by the tracker sensor noise, versus natural guide star magnitude. We compare the performance of a fast read-out, low noise CCD (5 e\(^{-}\) rms), and a quad-cell based on the new Slick\(^{TM}\) photon counting APDs, both sensing in R-band. We also compare the performance of a near infrared tracker, with a Nicmos array and of a NIR quad-cell based on APDs, sensing in the K-band. Although the NIR sensing has a disadvantage in the sky background and in the read-out/dark count noise, they are advantaged by the fact that the image to track upon is smaller and more diffraction limited, as nicely pointed out by Sandler et al.\(^4\). The tracker performance is computed here via the calculation of the rms error in the estimation of the tilt\(^5\), \(\sigma_{\theta}\):

\[
\sigma_{\theta}(\lambda) = \frac{\lambda}{D} \sqrt{\frac{\pi^2 + N}{N}} \left[ 4 \int_0^{\frac{\pi}{2}} e^{-\frac{\pi^2}{8}} \left( \frac{D}{r_{\text{eff}}(\lambda)} \right)^2 \left( 1 - x^2 \right)^{\frac{1}{4}} \arccos(x) + x (1 - x^2)^{\frac{3}{4}} \right] dx
\]

where D is the telescope diameter (3.5m in our case), \(\lambda\) is the tracker sensor operating wavelength (0.7 and 2.2 \mu m for the cases analyzed here), \(n\) is the sensor rms noise per pixel, which includes electronic noise, read-out noise, dark counts

<table>
<thead>
<tr>
<th></th>
<th>CCD (R-band)</th>
<th>APD (R-band)</th>
<th>NICMOS (K)</th>
<th>APD (K-band)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic Noise e(^{-}) rms /pxl</td>
<td>5</td>
<td>0</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Sky Background /pxl</td>
<td>0</td>
<td>0</td>
<td>176</td>
<td>176</td>
</tr>
<tr>
<td>integration time, seconds</td>
<td>0.008</td>
<td>0.008</td>
<td>0.033</td>
<td>0.033</td>
</tr>
<tr>
<td>effective QE</td>
<td>80%</td>
<td>80%</td>
<td>60% (^7)</td>
<td>60%</td>
</tr>
</tbody>
</table>

and sky background, if any, summed in the tracker integration time interval and for a 1.5 \lambda/D pixel angular size. N is the...
number of photons on the tracker sensor, and \( r_{\infty}(\lambda) \) is the effective Fried parameter, considering that partial high order correction is already done. The \( D/r_{\infty} \) values used are 3.8 and 1.6 at 0.7 and 2.2 \( \mu \)m operating wavelengths, respectively. The resulting values of the integral are 1.38 and 0.70, respectively, showing the advantage of sensing in the K band thanks to the better PSF Strehl values and size. This advantage has of course to compete with the higher noise and lower quantum efficiency of NIR sensors. This noise is computed assuming a sky background in K of 9000 photons/(m\(^2\)-sec-arcsec\(^2\)) and a pixel size of 0.24 arcsec, i.e. 3/2 of the diffraction limit in K. In the computations we have also used the assumptions of the above table.

Assuming that the core of the Airy profile of the star image on the tracker is gaussian, of \( \lambda/D \) FWHM, and that the tilt signal has a gaussian statistics, the long exposure Strehl Ratio contribution from tilt-jitter is given by:

\[
SR_{n}(\sigma_{\theta},\lambda) = \frac{1}{1 + \frac{\pi^2}{2} \left( \frac{D}{\lambda} \right)^2 \sigma_{\theta}^2}
\]

This time, \( \lambda \) is the science camera observing wavelength. Results in figure 1 are for a science camera observing in the K-band. The tracker sensing is done in R or K, and the star magnitudes refer to the tracking NGS, for the respective bands. K-band tracker sensing does not compare favorably with the R-band sensing. This apparently disagrees with similar calculations done for an AO system correcting in the NIR at an 8m telescope. However there is no real disagreement, the reason is due both to the fact that a 3.5m telescope has a larger diffraction limit PSF, and that the high order correction is quite good also in the visible R-band, for this 16x16 simulated AO system, hence the tracking star image is almost single speckled. The visible APD

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**Figure 1:** long exposure Strehl ratio values induced by tracker sensor noise effects, as function of star magnitude.
The advantage upon CCDs is evident for low light conditions, say above magnitude 16, when even 5σ rms read-out noise in the
CCD becomes important in the sensor S/N ratio. The level of Strehl ratio contribution from tilt jitter which can be tolerated
depends on the level of high order correction achieved, with realistic values in the range of 0.1 to 0.7.

3. Electronic Range Gating

When using a pulsed laser guide star (LGS) the Rayleigh backscatter may be used either for hybrid LGS systems or for single
copper vapor LGS. The upgoing beam is progressing at light speed, making 1 Km in 3.3 μsec. Currently range gating is done
using rotating wheels in front of fast read-out CCDs, with a resolution of about 1.5 Km. We have built in the APD circuitry
the gating and external triggering capabilities, in order to allow to sample the atmospheric backscatter with similar resolution.
Currently we have achieved experimentally a discrimination period of 35 nsec, which allow to get about 100 photons per Km
in a quad-cell APD based Shack-Hartmann (SH) sensor, with an option of slight improvement with new electronics components.
We find that 105 photons per pixel in such a SH sensor are sufficient to get 0.8 Strehl Ratio contribution from the wavefront
sensor noise, for the high order corrections of a 16x16 system on a 3.5m telescope. The advantage of such electronic gating,
coupled with the complete parallel readout of the APDs, can extend into multiple sampling of segments of the atmosphere,
monitoring and storing data from the upgoing beam, with potential advantages in multicollinear adaptive optics developments.
Possible optical schemes to implement this for the sodium LGS are under investigation.

4. Wavefront Sensor Transfer Function

We compare now the performance of a quad-cell-APD based Shack-Hartmann wavefront sensor with a frame transfer CCD
Shack Hartmann wavefront sensor. When an AO servo-system is studied in terms of its transfer function, it turns out that one
of the main limitations is in the net time delay of the CCD integration/read-out cycle. This is true particularly at operational
frequencies in the higher end, i.e. for short wavelength corrections, using NGS. The advantage of using APD based quad-cells
lies in the possibility of a direct parallel output of the N-S and E-W (tip-tilt) signals, filtered with a conventional two poles
filter, whose zeros may be selected according to the best operating tradeoffs. That is, the photon counts coming out of each
APD can be summed on a counter for a programmable integration period, which can be as short as 3.3 μm, and then sent either
directly to the Shack-Hartmann controller or else preprocessed in the quad-cell module controller, to get a continuous output
of the angle of arrival described by the mentioned analog two-poles filter.

To simulate this we use as input signal the one obtainable from the power spectrum of the angle of arrival of the starlet, that
is the wavefront phase derivative averaged over a SH subaperture. The power spectrum is described by a power law which has
two regimes, the lower end with a -2/3 exponent, and the higher end with a -11/3 exponent, delimited by a cutoff frequency
νc=0.3 v/dw, where v is the wind speed that we assume as 10m/s, and dw is the subaperture diameter which we assume 0.2m,
i.e. νc=15Hz. This input signal is fed into a 4-pixel quad-cell of a frame-transfer CCD, and we analyze the transfer function
of such a sensor for the integration times τo of 1, 4 and 20 msec, respectively. The assumed CCD frame readout time is τfo=1
msec. The CCD sensor transfer function in the Laplace transform space can be described as a function of the Laplace variable,
s, as:

$$H_{CCD}(s) = \frac{e^{-τ_p s}}{1 + \frac{τ_1 s}{2π}}$$

where τo=(τi+τfo)/2 is the delay due to integration times and readout, τi is the integration time, s is the usual Laplace
transform variable. The numerator of this function is a pure phase delay term, while the denominator is acting on both amplitude
and phase. We have tested numerically that this analytic representation is valid for the parameters ranges under test. As regards
the APD quad-cell, the transfer function at the end of the two-pole filter of the quad-cell module, again in Laplace variables,
can be described as:
\[ H_{APD}(s) = \frac{1}{s^2 + \frac{\zeta s}{2\pi f_n} + \frac{1}{\pi f_n}} \]

where \( f_n = 2 \text{KHz} \) is the natural damped frequency, and \( \zeta = 0.7 \) is the damping factor. Results in terms of amplitude and phase of the transfer function, as Bode plots, are expressed in fig. 2. CCD results are plotted for integration times of 20, 4 and 1 msec, respectively, as indicated in the figure legend. The upper section shows the drop in gain vs operating frequencies. The mentioned net loss of phase due to the integration time is evident in the lower plot, and it is the main CCD limitation that we have tried to overcome with this sensor design. In both amplitude and phase, the wavefront sensor transfer function for the CCD, limits the response function of the overall adaptive system, and the gain of the proposed solution is evident.
5. Implementation of APD electronics

APD electronics has been implemented so far in the most critical part, i.e. the quenching circuitry. The general built-in flexibilities and design requirements have already been described, however we repeat them here:

- control the APDs discrete array temperature via a cold finger in a dewar, kept at moderate low temperature (-40 C) instead of current Peltier thermocoolers close to the telescope focal plane;
- monitor the APD temperature in order to compensate the variation of the breakdown voltage, thus keeping the overvoltage and hence the effective QE constant;
- vary externally the overvoltage to get greater flexibility in terms of afterpulsing and effective QE control;
- vary externally the hold-off time to get greater flexibility in terms of afterpulsing control at low light regimes;
- provide external triggering and gating capabilities;
- achieve a very fast active quenching and reset times to allow for 30-40 nsec discrimination, for LGS use (electronic range gating, multiple layer sampling);
- have a programmable integration time, and get a 16 bit counts value directly, and/or get a filtered tilt signal continuous output with programmable filtering;
- have a safety switch for accidental light flashing when the APDs are in ready mode. Although they are not physically damaged by high light levels, they need afterwards sometime to recover the steady state performance.

Figure 3 shows the measured voltages at the APD connections, and illustrates the timing of the various phases, where a passive quenching (I) ignites the active quenching circuit (II), then the apd is kept for a certain hold-off time below the breakdown voltage (III), before being actively reset (IV) and ready to count for another photon.

![Figure 3: Voltage measured at the APD connections, showing the timing of the different steps of the quenching process.](image-url)
Figure 4 shows the APD quenching circuit output signal, where each count is a modified TTL pulse. The horizontal time scale is 10 nsec/div, while the vertical scale is at 0.5 V/div. It shows that the minimum discrimination of the counts is below 40 nsec. These values should improve slightly in the future with better components and removing parasitic capacitances, we aim at 33 nsec or less.

![Figure 4: Modified TTL output for photon counting, showing a discrimination of 38 nsec between counts.](image)

References:


5. G.Tyler and D.L.Fried: "Image Position Error Associated with a quadrant detector", JOSA A 72, 804-808, 1982

