A CCD BASED CURVATURE WAVEFRONT SENSOR FOR ADAPTIVE OPTICS IN ASTRONOMY

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Abstract: Advances in charge-coupled device (CCD) technology motivated an investigation of the use of a specially designed CCD as the wavefront sensor detector in a 60-element curvature AO system. A CCD has never been used before as the wavefront sensor in a low light level curvature adaptive optics system. A CCD can achieve nearly the same performance as APDs at a fraction of the cost and with reduced complexity for high order wavefront correction. Moreover the CCD has higher quantum efficiency and a greater dynamic range than APDs. A readout noise of less than 1.5 electrons at 4000 frames per second was achieved. A back-illuminated thinned version of this CCD can replace APDs as the best detector for high order curvature wavefront sensing.

Key words: CCD, APD, curvature sensing, adaptive optics, detectors

1. INTRODUCTION

Curvature AO-systems have traditionally used avalanche photo diodes (APDs) as detectors. APDs are photon-counting devices that produce a pulse on their output whenever a photon is detected. APDs have no read-out noise and read-out is almost instantaneous. However, they have some serious drawbacks compared to charge-coupled devices (CCDs): ***A Small dynamic range*** calls for the use of neutral density filters to adapt the incident photon flux to the dynamic range of the APD. CCDs, on the other hand, have an enormous dynamic range and thus require no filters. ***Low quantum efficiency***. APDs typically have a peak quantum efficiency of 70% at 700nm, while the same number for CCDs is over 90%. ***High dark current***.

APDs generate dark current, or false photon counts, of 100 to 250 counts per second depending on the cost of the APDs, while a well-cooled CCD generates a negligible amount of dark current. ***High cost***. A 60-element AO-system using APDs is significantly more expensive than one using a CCD.

2. ARCHITECTURE AND FUNCTIONALITY OF THE CURVATURE CCD

To summarize the design [1,2], the curvature CCDs consists of 80 integration areas (superpixels). Each superpixel consists of 20 x 20 pixels, where a pixel is 18 x 18 microns in size. The total height of each column is 10 superpixels or 200 pixels. There are 8 columns for a total of 80 superpixels and an independent tip/tilt sensor array. Very short exposure times (250 µsec) with "long" integration times (1 to 20 msec, 2 to 40 cycles of a 2 kHz membrane) are possible with the ability to switch between half-cycle integrations within 10 µsec and to store half-cycle frames on-chip while integrating other half-cycle frames. The read out time of all pixels is 250 µsec with the use of multiple readout ports to have slower readout rates and lower readout noise. BI devices will have high quantum efficiency (peak greater 80%).

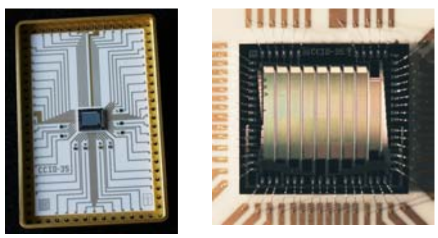

Figure 1. Pictures of the curvature CCD

3. PROTOTYPE SYSTEM AND CCD TEST RESULTS

To test the performance and the functionality of the curvature CCD, a laboratory system has been built to allow independent testing without the need to interface to a full adaptive optics system. An integrating sphere and a stable light source were used to simulate the membrane movement and providing the light signal for CCD characterization. An Oeffner relay optics was designed (consisting of two spherical, reflecting surfaces) to re-image the light of the fibers 1:1 onto the superpixels) and a fiberfeed with 60 individual fibers plus 4 additional fibers for the tip/tilt sensor to feed the subapertures of the CCD with light.

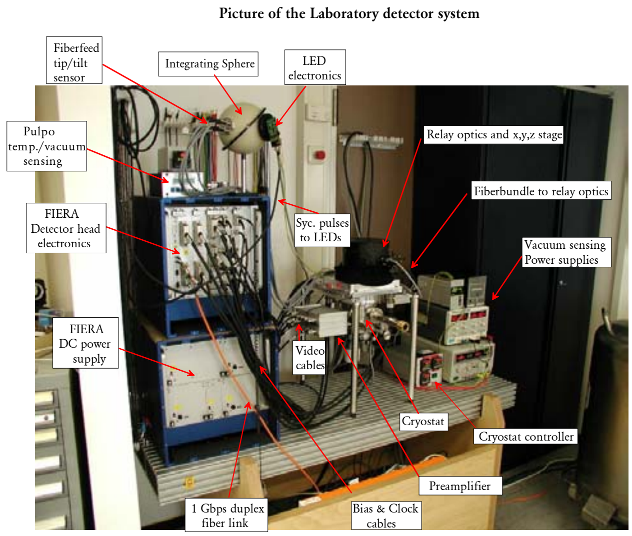

Figure 2. Prototype system of the CCD based curvature wavefront sensor

A readout noise of less than 1.5 electrons was achieved for all readout ports including the tip/tilt sensor at a readout speed of 4000 frames per second [1]. With all pixels per readout port binned into 12 superpixels, it was possible to read the serial register relatively slowly at 50 kilopixels per second. Vertical and horizontal CTE is better than 0.99999 down to lowest light levels. Residual non-linearity better than 0.5% / -0.5%. (peak to peak). Negligible amount of dark current at 197 Kelvin (0.25 electrons per subaperture at 50 Hz frame rate).

4. CCD PERFORMANCE COMPARED TO APDS

A common measure used to quantify the performance of an AO-system is the *Strehl ratio* of the corrected point spread function (PSF). To compare the performance of the CCD and APDs, a computer model of the atmosphere, telescope and AO-system was developed in MatLab. Using the computer model [1,3], the Strehl ratio in K-band was measured for guide stars of magnitude 10 to 18 and compared for the different detectors. The CCD performs as well as APDs over the entire range of magnitudes down to very faint guide stars at magnitude 18. The plot shows a small difference of the performance of the CCD of 3% at magnitude 15 compared to APDs

Table 1. Parameters for the Simulation

Property	APD	CCD
Sky background magnitude	19.0	19.0
Field of view diameter	2"	2"
Quantum efficiency	70%	80%
Dark current [electrons/s]	250	0
Read-out noise [electrons RMS]	0	1.5
Read-out delay [µs]	0	250
Seeing [arcsec]	0.65	0.65

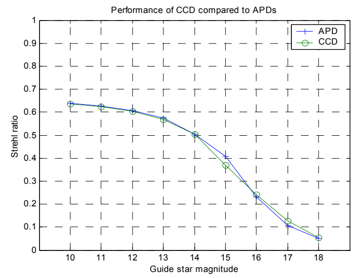

Figure 3. CCD performance compared to APDs

5. CONCLUSIONS

It can be concluded that the CCD achieves nearly the same performance as APDs. Thinned versions have the potential to work as well as APDs with reduced cost and reduced complexity. No neutral density filters are needed (simpler) and the CCD provides a much greater integration area per subaperture (360 µm by 360 µm). Moreover, the CCD has a higher quantum efficiency and a greater dynamic range (factor 1000) than APDs. A Readout noise of less than 1.5 electrons at 4000 frames/s has been demonstrated with the laboratory system. The curvature CCD combines high order curvature sensing with the possibility of separate tip/tilt sensing in one sensor and will be tested in the future at the CFHT telescope in the mainframe of the CFHT's FlyEyes project [4].

6. REFERENCES

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