A noiseless kilohertz frame rate imaging detector based on microchannel plates read out with the Medipix2 CMOS pixel chip

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Abstract

A new hybrid optical imaging detector is described that is being developed for the next generation adaptive optics (AO) wavefront sensors (WFS) for ground-based telescopes. The detector consists of a photocathode and proximity focused microchannel plates (MCPs) read out by the Medipix2 CMOS pixel ASIC. Each pixel of the Medipix2 device measures 55×55 μm^2 and comprises pre-amplifier, a window discriminator and a 14-bit counter. The 256×256 Medipix2 array can be read out noiselessly in 287 μs. The readout can be electronically shuttered down to a temporal window of a few μs. The Medipix2 is buttable on 3 sides to produce $512\times$(n*256) pixel devices. Measurements with ultraviolet light yield a spatial resolution of the detector at the Nyquist limit. Sub-pixel resolution can be achieved using centroiding algorithms. For the AO application, very high continuous frame rates of the order of 1 kHz are required for a matrix of 512×512 pixels. The design concepts of a parallel readout board are presented that will allow this fast data throughput. The development status of the optical WFS tube is also explained.

Key words: adaptive optics, wavefront sensor, photon counting, CMOS pixel chip, microchannel plate detector, kHz frame rate.
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1 Introduction

The future of ground-based astronomy in the optical and infrared spectral regions relies on the advancements in adaptive optics (AO) to overcome the limitations that the atmosphere places on high resolution imaging. Temperature gradients due to turbulence yield slightly different refractive indices of the patches of air that the wavefronts traverse. Consequently, the resulting phase errors give rise to a blurred image at the telescope focal plane. A key technology for AO systems on future very large telescopes are the wavefront sensors (WFS) which detect the optical phase error and send corrections to deformable mirrors [1].

One of the methods to determine the amount of the optical phase error due to atmospheric turbulence is called 'Shack-Hartmann' wavefront sensing. It consists of a lenslet array positioned above a focal plane detector array (the WFS). Each lenslet is calibrated such that a plane wave incident on it will focus in a spot on the center of a few pixels, the spot positions being uniformly spaced in both directions. As tilt is introduced by the atmosphere into this incident wavefront, the spots shift. The direction and degree to which each spot shifts from the center can be translated into the approximate incident phase angles.

The next generation of planned telescopes with >30 m diameters will therefore require WFS that have large pixel formats (512×512) to determine with high precision the position of around 5000 spots, which provide the steering information of the same number of mirror segments that compose the deformable mirrors. Moreover, low noise (<3 e^-/pixel) and very high frame rates ($\sim$1 kHz) are essential [2]. These requirements have led to the idea of a bare CMOS active pixel device (the Medipix2 chip) functioning in counting mode as an anode with noiseless readout for a microchannel plate detector at 1 kHz continuous frame rate.

2 A photon counting optical pixel detector

In order to cope with the stringent requirements for the next generation of WFS for AO, we propose the following detector integrated in a vacuum tube:

- a photocathode with high quantum efficiency (QE) in the visible
- two microchannel plates (MCPs) in "chevron" configuration
- 2×2 Medipix2 event counting ASICs

In the **photocathode** the impinging photon releases a photoelectron. Up to now photocathodes in the optical showed only very modest QE, but progress in material development opens new application fields. Developments in com-

mercial night vision tubes have demonstrated photocathode QE of >40% in the optical with GaAs photocathodes [3]. GaAsP photocathodes have been shown to even exceed 50% [4].
The released photoelectron is proximity focused onto a matched pair of **MCPs**, where the charge signal is amplified. MCPs consist of an array of pores with high secondary electron emission coefficient in a specialized glass substrate. Applying a high voltage across the MCPs, the accelerated electron hits the pore wall releasing secondary electrons and finally causes an avalanche that exits the rear surface of the MCP. MCPs combine high spatial resolution (pore diameters range from 2 μm upwards), high gain (tunable from a few 10^3 to a few 10^6) and excellent timing resolution in the range of hundreds of ps.
The new concept of our proposed WFS consists in the way the charge cloud that exits the MCPs is detected. The anode of our WFS detector will be composed of an array of 2×2 **Medipix2 CMOS photon counting pixel chips** developed in the framework of the Medipix2 Collaboration [5]. The Medipix2 chip consists of a matrix of 256×256 square pixels of 55 μm pitch, buttable on 3 sides. Each pixel comprises a charge-sensitive preamplifier, an upper and lower discriminator that can be used to select a signal window, and a 14-bit counter [6]. Each pixel can be masked and tested electrically with a calibration pulse. Both thresholds can be tuned with 3 bits. The measured equivalent input noise of Medipix2 is 100 e^- rms, the same as the residual threshold variation after tuning. Typical threshold values are $\sim$2000 e^-. Because of the high ratio of threshold to noise there are no noise hits in the absence of an input signal. For an acquisition, a programmable shutter signal is applied; as soon as the signal goes high again, readout starts. This shutter signal can be used to gate laser guide stars, artificial reference stars used for the Shack-Hartmann correction. The chip can either be read out serially or using a parallel CMOS bus. In the latter case the complete matrix can be shifted out within 287 μs (at 100 MHz). Unlike CCD sensors, the readout process is completely noise-free as it is only a matter of shifting the counter bits out of the chip (fully digital readout).

3 First measurement results with UV photons

Before constructing an optical tube with a photocathode, we decided to investigate the performance of our new detector with a flexible setup involving a vacuum chamber with a quartz window and a simple UV pen-ray lamp [1]. The MCP pair and a Medipix2 chip were placed inside the vacuum chamber. The high voltage and therefore MCP gain could be varied as well as the distance of the MCP exit face to the Medipix2 chip and the acceleration voltage across

[1] Bare MCPs have a small residual sensitivity of the order of 10^{-6} to UV light.

this gap. This setup allows the optimization of the different parameters for the AO application without having to build a new tube. Each UV photon that gets detected by the MCP yields an electron cloud at the MCP exit that is subsequently processed by the Medipix2 chip. The result is a 'spot' whose diameter depends on the MCP gain, the Medipix2 threshold and the field across the MCP-Medipix2 gap.
The first feasibility tests proved to be very successful. Obtained images have already been published [7],[8]. Except for some MCP features like dead spots or multi-fiber structures no fixed pattern noise could be detected. One can correct for the mentioned features (as they are stationary) by applying a flat field correction. The measured resolution using a resolution test pattern was 9 lp/mm (line pairs per mm) corresponding to the Nyquist limit, the theoretical resolution given by the 55 μm Medipix2 pixel size. Sub-pixel resolution can be achieved if the flux is limited to $<\sim$150 events/frame such that only single, non-overlapping events are detected and individual event centroids are determined by calculation off-chip. Sub-pixel resolution of 18 lp/mm corresponding to a 28 μm pixel size has been demonstrated [8]. This latter result is not of use for the high-rate AO application, but may be interesting for other low-rate imaging applications.
To simulate the response of a Shack-Hartmann WFS, a pinhole mask with holes of 10 μm diameter at 500 μm spacing in both directions was fixed above the MCPs. The UV pen-ray lamp simulated the reference star and produced approximately 700 pseudo-stellar images on the detector (see left Fig. 1) [2]. Data was acquired with a MCP gain of about 60 ke$^-$ per detected photon and 1600 V/500 μm rear field to restrict the lateral spread of the charge cloud exiting the MCPs. The 25 s integration time resulted in about 600 photons per spot. Each data run consisted of two integrations taken at each of the 11 lamp locations and aimed at investigating the spot movement. The x and y locations of each spot were found by fitting a Gaussian to the x and y profiles of a 9×9 pixel area surrounding each spot. For each lamp offset the location of each spot was compared to its location in the first image (the 0 mm lamp position) and the x- and y-shifts calculated. The result is plotted in Fig. 1 (right) and shows the good sub-pixel spatial linearity of the detector in both directions [3]. The measurement points for each lamp location correspond to the fitted value of the shift for all 700 spots at this position; the sigma of these distributions ranged between 2 and 4 μm only. This sigma variation had a frequency of exactly 55 μm (the pixel pitch) and is due to undersampling. It disappears with lower rear field and therefore larger spot sizes.

[2] The white areas in this image are due to blocked pinholes by kapton tape on the image mask, and the black line corresponds to one defective Medipix2 column.
[3] The pinhole mask was slightly rotated relative to the Medipix2 pixel arrangement resulting in a different slope for the two curves.

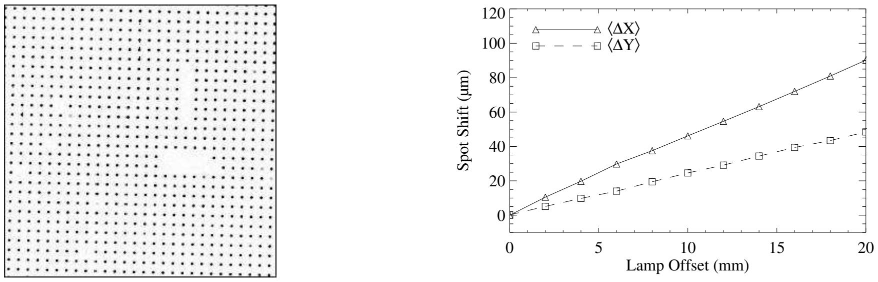

Fig. 1. Left: Image obtained with a uniformly spaced pinhole array of 10 μm diameter pores. The UV lamp simulated the guide star and the image mask the lenslet array used with Shack-Hartmann WFS. Right: x- and y-shifts for the 700 spots at each lamp location show a good linear response. The width of the 700-spot distributions amounted on average to only 3 μm.

4 Fabrication of the optical tube

Fabrication of the optical tube is underway; as a first stage the tube will only contain one Medipix2 chip. A ceramic header has been designed that will incorporate a ground plane where the Medipix2 chip will be glued to, as well as bonding pads and traces on the inside and passive components and connectors on the outside. A kovar weld ring will be brazed to this ceramic header. The Medipix2 ASIC is glued to the header with conductive epoxy and the Medipix2 pads wire-bonded to the traces. Pre-weld tests of this assembly will be performed. The next steps consist of laser welding the assembly into the back-end of the brazed tube body and installation of the MCPs into the tube followed by functional testing. After some further processing steps, the tube will be sealed with the semi-transparent GaAs photocathode window. The mounting of the connectors and capacitors for decoupling will finalize the optical tube. Fig. 2 shows the complete tube assembly that will be very compact with a diameter of 34 mm and a height of 12.7 mm. The tube will be connected to the parallel readout board via a 4-layer flex-rigid circuit.

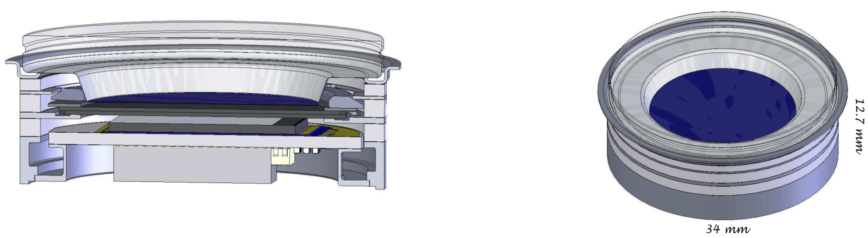

Fig. 2. In the left image the different components of the optical tube are shown (photocathode, MCP pair, Medipix2 chip, alumina substrate and connectors). A sketch of the final tube with outer dimensions of 34 mm x 12.7 mm is presented in the image at the right.

5 A kHz frame rate readout for a 260k pixel detector

The main challenge for a new-generation WFS is the high **continuous** frame rate in the kHz range of a large pixel array combined with a superb noise performance for a precise centroid determination. This high frame rate is required in AO correction to temporally oversample the atmospheric turbulence induced phase shifts.

With such high frame-rate applications in mind, a data readout board, referred to as 'PRIAM' (Parallel Readout Image Acquisition for Medipix), is being developed at ESRF Grenoble for data acquisition at kHz frame rate with the Medipix2 chip. This board provides five 32-bit parallel input ports allowing the simultaneous readout of up to five Medipix2 chips in less than 290 μs. The data (14 bits per pixel) are first buffered in fast FIFOs and then processed on-line in a FPGA circuit clocked at 100 MHz. The main processing steps are pixel data decoding using a look-up table, geometrical pixel rearrangement, and optional dead time corrections [4] . An on-board memory stores the threshold calibration masks as well as other data for on-line flatfield correction or other purposes. The board controls all the Medipix2 features except the charge sharing test signals (analog outputs of 3×3 pixels per Medipix2 chip). Specific data reduction algorithms can be implemented in the FPGA.

In the case of the adaptive optics application, the images consisting of an array of about 5000 spots will be processed to extract the centroid coordinates and the variance of each spot. This is the information needed to steer the actuators that move the segments of the deformable mirror. The board provides four bi-directional serial links of 1.6 Gbit/s data bandwidth, each interfacing to one PC control system. Using only one serial port, the minimum readout time will be 660 μs/chip, defined by the FPGA clock frequency. This will allow to reach a kHz frame rate for a single chip module. Using four serial I/O ports in parallel, it will be possible to achieve kHz frame rates for a 4-chip module. However this requires a more complex computer system and will be implemented only in a second step.

6 Conclusions

The proposal for a new-generation wave front sensor for adaptive optics has been presented. The detector consists of a high-QE photocathode and a MCP pair in chevron configuration read out with the Medipix2 photon counting chip. This concept should allow the production of a 260k pixel detector, read out noiselessly and continuously at a 1 kHz continuous frame rate. The spatial

[4] The dead time of the pixel detector corresponds to the time needed to transfer all the counter values into the FIFOs, max. 290 μs.

resolution of this detector has been determined to be the Nyquist frequency, and good sub-pixel linearity was shown. The measured dynamic range of one Medipix2 chip ranged from a few counts per second to about 500M counts per second. The design of the compact optical tube that is about to be fabricated has been explained. To reach the aim of continuous 1 kHz frame rate operation, a new parallel readout board is in its final production stage.

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