Orthogonal Transfer Arrays for Wide-Field Adaptive Imaging[†]

Barry E. Burke[a]*, John L. Tonry[b], Michael J. Cooper[a], Peter E. Doherty[a], Andrew H. Loomis[a], Douglas J. Young[a], and Peter Onaka[b]
[a]MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA USA 02421
[b]Institute for Astronomy, University of Hawaii, Honolulu, HI USA 96822

The orthogonal transfer array (OTA) is a novel charge-coupled device (CCD) imager based on the orthogonal-transfer CCD (OTCCD). The OTCCD, in turn, is a device capable of charge transfer in all directions and has been developed for adaptive imaging in ground-based astronomy. By using a bright guide star as a beacon, the OTCCD can correct for wavefront tilt due to atmospheric effects as well as compensation for telescope shake, which in turn enhances the resolution and SNR [1]. However, for wide field-of-view imaging the atmospheric wavefront distortions decorrelate over distances more than a few 10's of arcmin and hence an array of independently driven OTCCDs is required.

To resolve this issue we developed the OTA, which consists of a two-dimensional array of OTCCDs combined with addressing and control logic to enable independent clocking of each OTCCD. This device enables spatially varying electronic tip-tilt correction and was developed for the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) program at the University of Hawaii Institute for Astronomy (UH/IfA) [2]. The basic architecture is illustrated in Figure 1, and features an 8×8 array of OTCCDs on a 50×50-mm die. Figure 2 describes the individual OTCCD, or cell, comprising a 590×598-pixel imaging array of 10-µm pixels, serial register and readout circuit. A small block of NMOS logic controls the parallel clock drive to each OTCCD and the schematic for this logic is shown in Figure 3.

Each logic block is addressed by a row and column select line and accepts three data bits, D0–D2. These bits in turn set the state of three lines, Z0–Z2, which are connected to pass transistors that in turn control the parallel clocks and video output. Line Z1 enables four parallel clocks from off-chip drivers to be applied to the gates, while Z0 sets the gates in a standby state with two phases (1, 2) high and the remaining two low. During image readout, Z1 and Z2 are high, but only one cell in a column can be read out at a time since all eight cells in a column share a video output bus.

The device operation consists of about 30 s? of image acquisition followed by a readout period. During the integration period the parallel clocks of each cell must perform pixel shifts to track the image motion. To measure the local wavefront tilt, a small subset of cells (up to 5) in an OTA are used to image bright guide stars at rates up to 30 Hz. From the image deflection data of these star images, the optimum pixel shifts for the remaining cells ("science cells") can be computed. Each of the science cells is addressed sequentially and the appropriate pixel shift applied. At the end of the image acquisition time, the science imagery is read out one row at a time. A two-stage amplifier at the output of each cell provides sufficient drive for read rates greater than 1 Mpixel/s.

Two important performance measures for this device are high quantum efficiency, especially in the I band (730-900 nm) and small charge point-spread function (PSF). This necessitates the use of thick, high-resistivity material with a design that enables substrate bias. The OTA is fabricated on p-type, 150-mm wafers having a resistivity of 5 000 Ω·cm or greater. Figure 4 illustrates in cross section the features that enable such a capability. The back surface, which is a thin p^+ layer, is biased from the front of the device via an undepleted path around the device perimeter. To prevent excessive front-to-back hole current, the channel stops are narrow and the remaining non-active device area filled with an n+ doped layer biased to a positive potential [3]. This approach has another feature of interest, namely, it effectively isolates the ground reference of the CCD from the logic. This in turn allows us to bias the logic, which passes the parallel clocks to the pixels, below ground. This is favorable for the performance of buried channel CCDs in terms of well capacity and charge-transfer efficiency. We typically use low parallel clock rails of -3 to -6 V. The serial clocks come directly from off-chip drivers and therefore are likewise not constrained as to voltage rails.

The advantages of substrate bias can be seen clearly in Figures 5 and 6. Figure 5 shows the improvement in RMS charge spreading with substrate bias. For Pan-STARRS the goal is less than 4 µm. Figure 6 shows the improved quantum

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* bburke@ll.mit.edu.

efficiency resulting from an increase in device thickness from 45 μm (our standard for non-substrate biased devices) to 75 μm. The device has a two-layer anti-reflection coating optimized for the visible/near IR with a reflectivity null near 850 nm. This coating and the increased device thickness virtually eliminates the problematical Fabry-Perot “fringing” from sky glow.

Figure 7 is an image taken with a back-illuminated OTA at -70˚C. The device comprises 22.6 Mpixels, and the fill factor is 0.90.

A photo of a front-illuminated packaged device is shown in Figure 8. The package base is made of Mo, and attached to it are three mounting legs and a custom multi-layer ceramic pin-grid array (PGA). A narrow lip of this ceramic appears at one edge of the Mo base and contains wirebond landings for the 99 device pads. The PGA is located beneath the package and is not visible in this photo. All the device I/O is carried to the support electronics via a flexprint that is press-fitted onto the PGA.

The program goal is a focal-plane array of 64 OTAs comprising collectively about 1.4 Gpixels, as illustrated in Figure 9. The devices for this focal plane array have been fabricated and packaged, and the assembly of the array is expected to begin this summer. As a stepping stone to the final Pan-STARRS focal plane, a 4×4 array of OTAs from a prototype lot has been assembled and is undergoing testing on the first of the four Pan-STARRS telescopes. A photo taken during the assembly of this array is shown in Figure 10.

References:

[1] J. L. Tonry , B. E. Burke and P. L. Schechter, "The Orthogonal Transfer CCD," Publications of the Astronomical Society of the Pacific, vol. 109, pp.1154-1164, October 1997.

[2] J. L. Tonry, P. M. Onaka, B. E. Burke, and G. A. Luppino, “Pan-STARRS and Gigapixel Cameras,” in *Scientific Detectors for Astronomy*, J. Beletic et al. eds., Springer, pp. 53-62, 2005.

[3] B. E. Burke, J. A Gregory, A. H. Loomis, M. Lesser, M. W. Bautz, S. E. Kissel, D. D. Rathman, R. M. Osgood III, M. J. Cooper, T. A. Lind, and G. R. Ricker, “CCD Soft-X-Ray Detectors with Improved High- and Low-Energy Performance,” IEEE Trans. Nuclear Science, vol. 51, 2322 - 2327, October 2004.

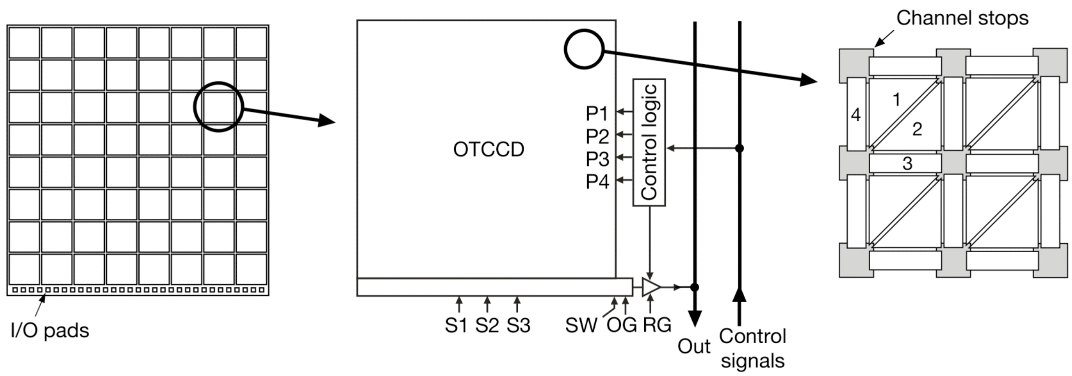

Figure 1. Depiction of the OTA. Each of the 64 cells consists of an OTCCD with 590(V)×598(H) pixels and a serial readout register. The parallel shifting and multiplexing of the video output of each cell is controlled by a logic block. The drawing on the right illustrates the arrangement of the four-phase CCD gates.

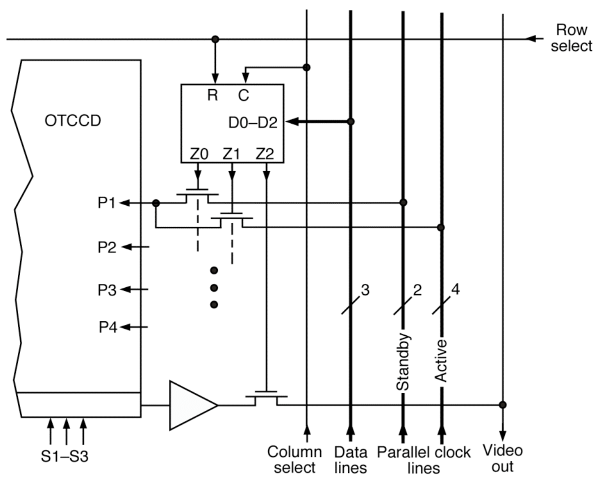

Figure 2. Schematic of the OTA cell and logic control.

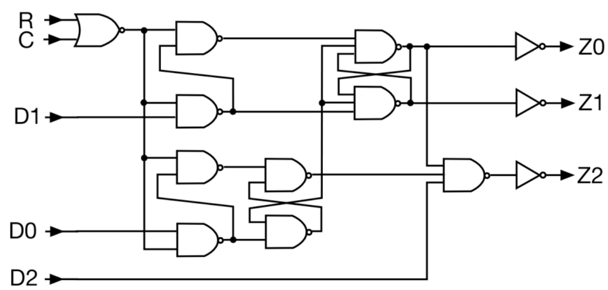

Figure 3. Control logic design used on the OTA.

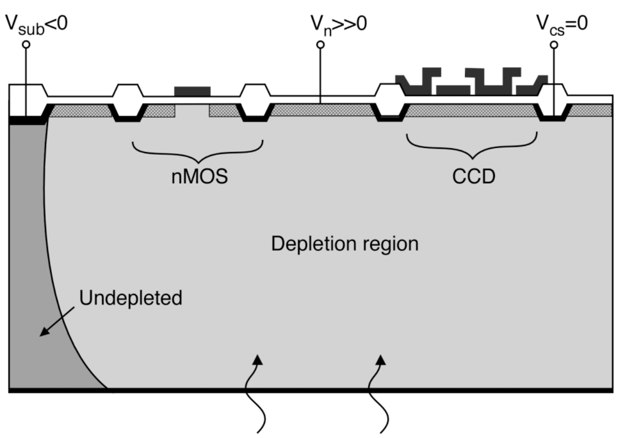

Figure 4. Cross section of OTA with substrate bias capability.

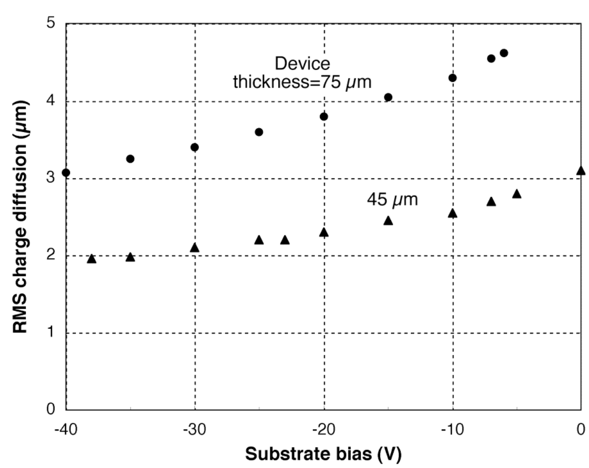

Figure 5. RMS charge diffusion vs. substrate bias for devices of two thicknesses.

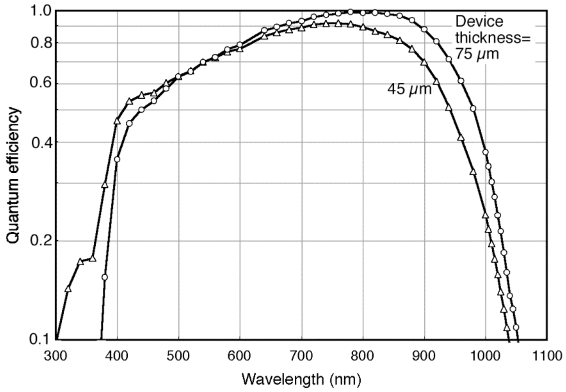

Figure 6. Quantum efficiency vs. wavelength at -70˚C for devices of 45 and 75 µm thickness.

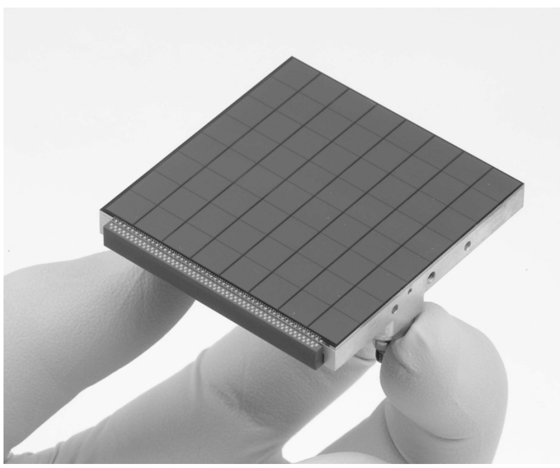

Figure 8. Photo of a packaged front-illuminated OTA.

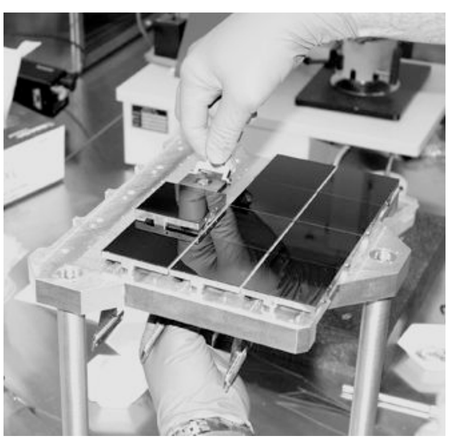

Figure 10. Photograph of the assembly of a 4×4 prototype focal plane array of OTAs for intital tests on the first Pan-STARRS telescope.

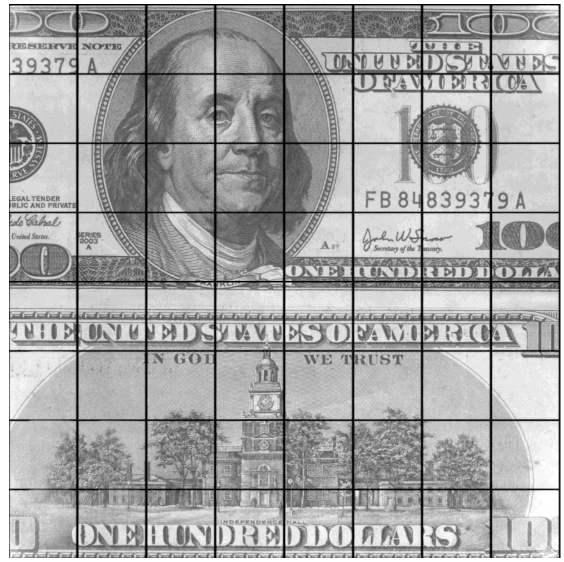

Figure 7. Image from a back-illuminated OTA (22.6 Mpixels) at -70˚C.

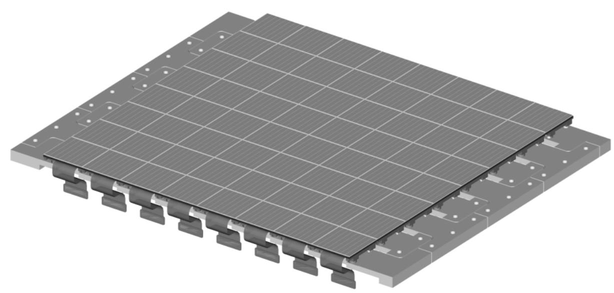

Figure 9. Depiction of the full 8×8, 1.4 Gpixel focal-plane array for Pan-STARRS.