Fast sub-electron detectors review for interferometry

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ABSTRACT

New disruptive technologies are now emerging for detectors dedicated to interferometry. The detectors needed for this kind of applications need antonymic characteristics: the detector noise must be very low, especially when the signal is dispersed but at the same time must also sample the fast temporal characteristics of the signal. This paper describes the new fast low noise technologies that have been recently developed for interferometry and adaptive optics.
The first technology is the Avalanche PhotoDiode (APD) infrared arrays made of HgCdTe. In this paper are presented the two programs that have been developed in that field: the Selex Saphira 320x256 [1] and the 320x255 RAPID detectors developed by Sofradir/CEA LETI in France [2],[3], [4]. Status of these two programs and future developments are presented. Sub-electron noise can now be achieved in the infrared using this technology. The exceptional characteristics of HgCdTe APDs are due to a nearly exclusive impaction ionization of the electrons, and this is why these devices have been called "electrons avalanche photodiodes" or e-APDs. These characteristics have inspired a large effort in developing focal plan arrays using HgCdTe APDs for low photon number applications such as active imaging in gated mode (2D) and/or with direct time of flight detection (3D imaging) and, more recently, passive imaging for infrared wave front correction and fringe tracking in astronomical observations. In addition, a commercial camera solution called C-RED, based on Selex Saphira and commercialized by First Light Imaging [5], is presented here.
Some groups are also working with instruments in the visible. In that case, another disruptive technology is showing outstanding performances: the Electron Multiplying CCDs (EMCCD) developed mainly by e2v technologies in UK. The OCAM2 camera, commercialized by First Light Imaging [5], uses the 240x240 EMMCD from e2v and is successfully implemented on the VEGA instrument on the CHARA interferometer (US) by the Lagrange laboratory from Observatoire de la Cote d'Azur. By operating the detector at gain 1000, the readout noise is as low as 0.1 e and data can be analyzed with a better contrast in photon counting mode.

Keywords: Adaptive optics, EMCCD, Avalanche photodiodes, APD, HgCdTe, SAPHIRA, SELEX, wavefront sensor, infrared sub-electron noise, photon counting.

1. INTRODUCTION

Developed by First Light Imaging and based on the Saphira detector developed by Selex for ESO, the C-RED infrared camera is opening a new era in terms of sensitivity and speed in the SWIR scientific cameras domain and is particularly suited for infrared wavefront sensing in complex AO systems like MCAO. This is in strong contrast to what is observed in APDs made out of III-V material or Si, which requires high inverse bias and have typical noise factors of F~4-5 for III-V semi-conductors and F~2-3 for Si respectively. These exceptional characteristics of HgCdTe APDs are due to a nearly exclusive impaction ionization of the electrons, why these devices have been called electrons avalanche photodiodes, e-

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APDs [6]. The next section presents the two main programs (RAPID and SAPHIRA) that have been developed around this new disruptive technology.

2. THE RAPID E-APD INFRARED WAVEFRONT SENSING DETECTOR

2.1 Presentation of the RAPID research program

Developed by the SOFRADIR and CEA/LETI manufacturers, the RAPID infrared detector offers a 320x255 8 outputs 30 microns e-APD array, sensitive from 0.4 to 3.3 microns, with less than 2 e readout noise at 1600 fps. Advanced packaging with miniature cryostat using pulse tube cryocoolers was developed in the frame of this programme in order to allow use on this detector in any type of environment. In 2013, the partners delivered the first prototypes and, given the performance results of these prototypes, the decision was quickly taken to push for an on-sky demonstration on a demanding instrument. PIONIER was chosen as its interferometric combination of light requires a very fast detector to fight against atmospheric turbulence, and a minimum amount of noise in order to detect faint objects. The RAPID detector is now implemented on the PIONIER [7] instrument on the ESO/VLTI interferometer in Paranal since December 2014. Since this time, RAPID observed more than 150 stars during more than 45 nights on the VLTI with a tremendous gain compared the previous camera based on conventional IR detectors.

2.2 The RAPID 320x255 pixel e-APD array presentation

The RAPID programme was a 4 years R&D project funded by the French "Fonds Unique Interministériel" in 2009. It includes several industrial and academic partners from the field of advanced infrared focal plane arrays fabrication (SOFRADIR, CEA-LETI) and of astronomical/defense institutes (IPAG, LAM, ONERA). The goal of this programme is to develop a fast and low noise infrared focal plane array of moderate format for astronomical fast applications. This research programme is currently ongoing with FOCUS funding.

The main characteristics of RAPID are:

- Pixels Format: 320 x 255 pixels 30µm pitch
- Technology: HgCdTe, intra-pixel CDS and CTIA, sensitive from the visible to 3- 3.3 µm @ 77K
- Rectangular window can be defined with the start line and the end line of the window to be read.
- Noise: less than 2 e.
- Frame rate: 1500 Hz, up to 2 000 Hz
- Dark signal: 100 e-/s measured, limited by setup background
- Power consumption: 122 mW

The goal of the RAPID development was to demonstrate operation of the 320x255 pixels 30 microns pitch infrared array at 2000 fps with less than 2 e- readout noise. To achieve such readout noise and fast frame rate, APDs technology and intra-pixel Correlated Double Sampling were both needed. The floor plan of the device is shown in the Fig. 1, it includes 8 parallel outputs clocked at 20 MHz pixel rate defining 8 stripes of 40x256 pixels with one amplifier per stripe. The detector can be seen in the Fig. 2 during its integration in the pulse tube cryostat.

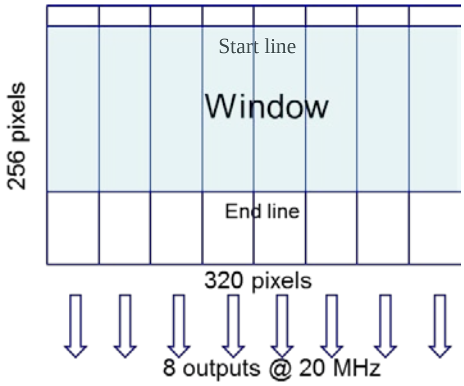

Fig. 1: The 1.6 kfps RAPID e-APD infrared detector configuration: 8 outputs 320 x 255 pixels with 30 µm pitch. A rectangular window with programmable start line and end line can be defined to speed up the frame rate.

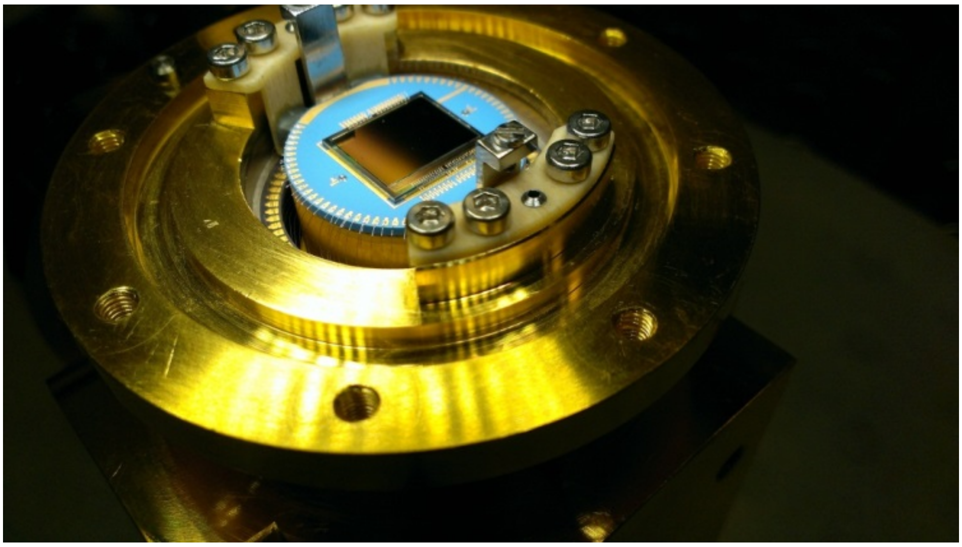

Fig. 2: The RAPID 320x255 IR APD array during integration by Sofradir in its cryostat cooled with a miniature pulse tube developed by the RAPID programme.

2.3 RAPID detector results

The best performances compromise for RAPID was to use 3.3 µm cutoff photodiodes providing multiplication gain exceeding 25 and providing readout noise below 2 e. The current readout circuit of the detector limits the photodiode polarization to 8V.

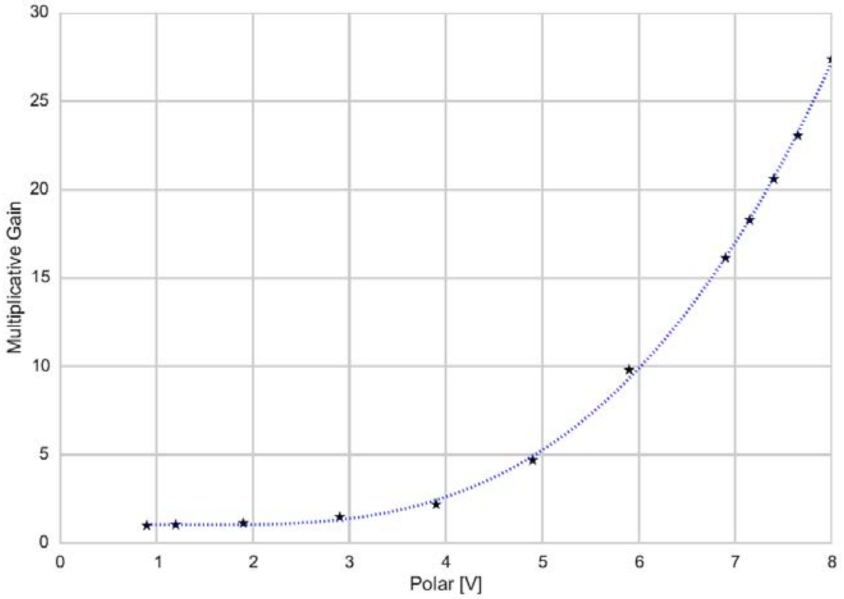

Fig. 3: mean multiplication gain of the APD array as a function of the photodiode polarization voltage for 3.3 µm photodiodes cut-off.

The Fig. 3 shows the multiplication gain as function of the photodiode voltage for the RAPID 3.3 µm cut-off array. As the cut-off wavelength is large, this allows to obtain high multiplication gain for a modest photodiode polarization. Sub-e readout noise for the maximum photodiode polarization can then be measured as it can be seen in the Fig. 4.

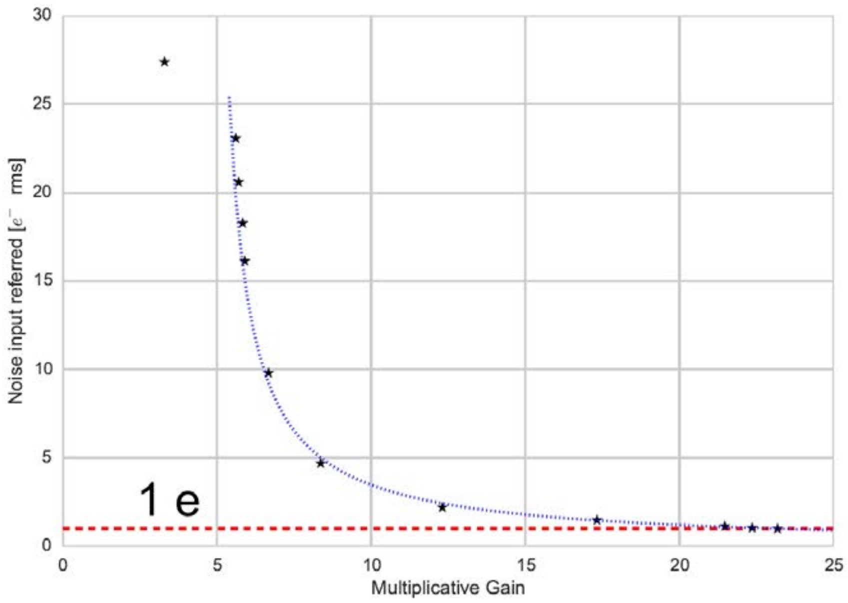

Fig. 4: mean readout noise as a function of the multiplication for RAPID array with 3.3 µm cut-off.

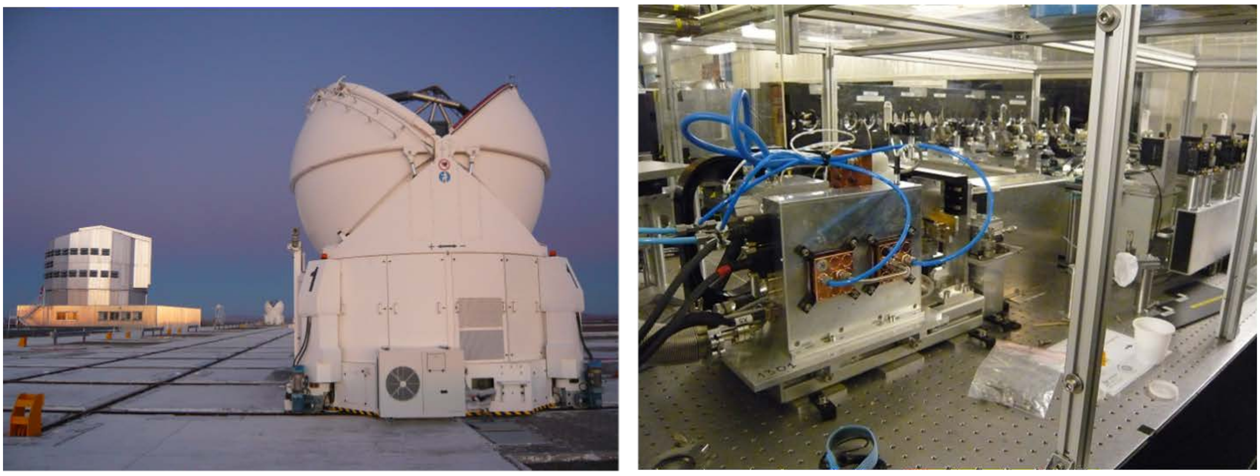

Fig. 5: the RAPID APD array installed on the ESO VLTI Pionier instrument.

The Fig. 5 shows the RAPID camera integrated on the PIONIER instrument [7] in December 2014. The PIONIER instrument is combining the light from the 4 VLTI Auxiliary Telescopes in Paranal. The RAPID camera is producing scientific observation for this instrument since this date. The Fig. 6 shows the RAPID readout noise histogram with a multiplication gain of 25, demonstrating that a median readout noise of 0.75 e noise at 1600 fps was routinely measured while the camera was operated on the telescope.

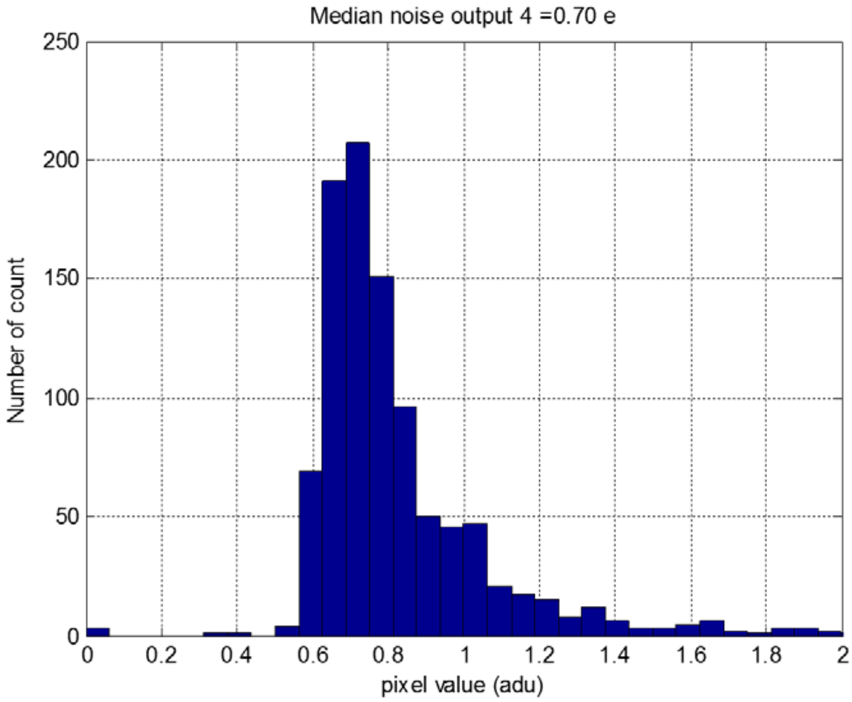

Fig. 6: the RAPID noise histogram as measured in Paranal (ESO, Chile) on the PIONIER ESO/VLTI instrument. The median noise measured here is 0.7 e for a multiplication gain of x25. The detector temperature is 75 K and the frame rate is 1600 fps.

3. THE C-RED ONE INFRARED APD CAMERA FROM FIRST LIGHT IMAGING

3.1 The C-RED one infrared APD camera presentation

C-RED is the only one commercial infrared camera using the Selex Saphira 320×256 pixels HgCdTe e-APD array with 24 microns pixel pitch. C-RED is developed by First Light Imaging [5]. The sensor cutoff wavelength is 2.5 microns and it allows sub-electron readout noise, taking advantage of the e-APD noise-free multiplication gain and non destructive readout ability. C-RED is also capable of multiple regions of interest (ROI) readout allowing faster image rate (10's of KHz) while maintaining unprecedented sub-electron readout noise.

The sensor is placed in a sealed vacuum environment and cooled down to cryogenic temperature (70K) using an integrated pulse tube, with a high reliability (MTBF > 90 000 h) much higher than standard Stirling coolers used usually with cooled infrared arrays.

The Fig. 7 shows a picture of the C-RED one camera prototype. The commercial camera will include a special housing, not shown in this figure, to protect the fragile components of the system and to avoid water condensation inside the camera. On top of the camera, the helium compressor for cooling the pulse tube can be seen on this figure.

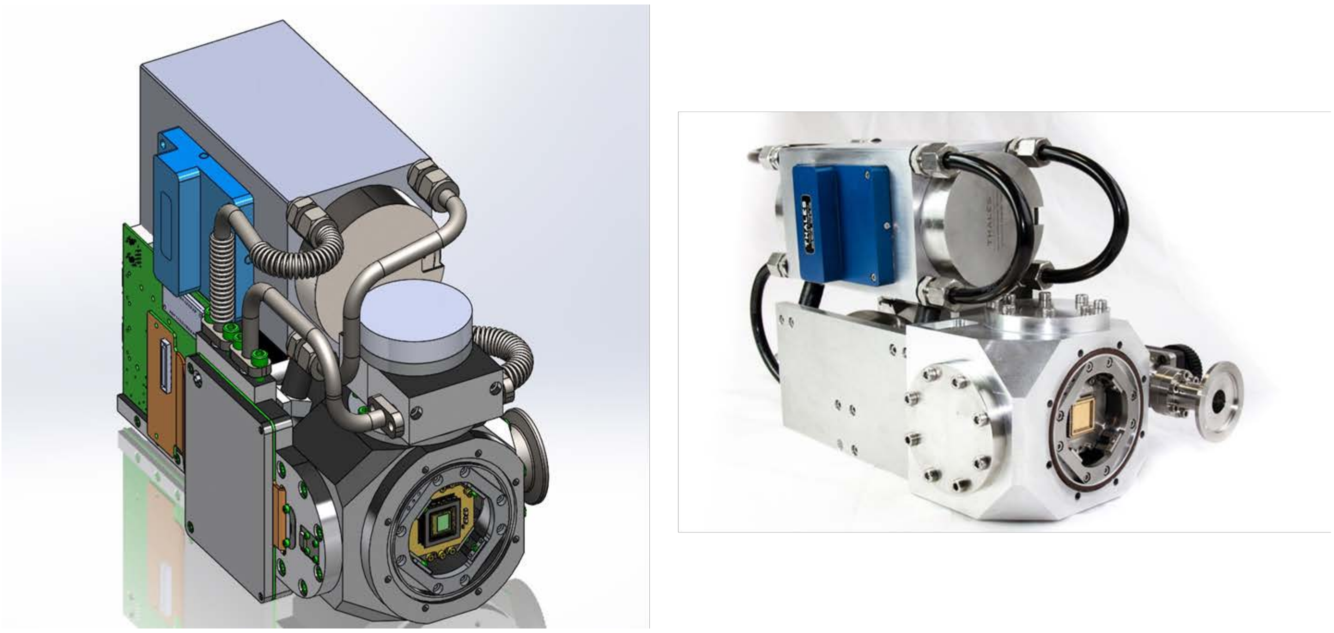

Fig. 7: the C-RED one infrared camera commercialized by First Light Imaging and that uses the Selex Saphira infrared array.

3.2 The Selex Saphira detector of C-RED one.

Designed and fabricated by Selex, the Saphira detector is designed for high speed infrared applications and is the result of a development programme alongside the European Southern Observatory on sensors for astronomical instruments. It delivers world leading photon sensitivity of <1 photon rms with Fowler sampling and high speed non-destructive readout (>10K frame/s). Saphira is an HgCdTe avalanche photodiode (APD) array incorporating a full custom ROIC for applications in the 1 to 2.5µm range.

Like the RAPID detector, SAPHIRA use the HgCdTe APD properties, offering sub-electron noise with multiplication gain up to x80. The pixel format is 320x256 pixels with 15fF integration node capacitance (30fF with HgCdTe diode). The array has 32 parallel video outputs, organized as 32 sequential pixels in row. The 32 outputs are arranged in such a way that the full multiplex advantage is available also for small sub-windows. Non-destructive readout schemes with subpixel sampling are possible. This reduces the readout noise at high APD gain well below the sub-electron level at frame rates of

1 KHz. The growth technology used now is the metal organic vapour phase epitaxy (MOVPE). This growth technology provides more flexibility for the design of diode structures. It is possible to make heterojunctions with different bandgap properties between the absorption region and the multiplication region. The change to MOVPE resulted in a dramatic improvement in the cosmetic quality with 99.97 % operable pixels at an operating temperature of 85K. The avalanche gain is controlled by an external voltage. The digital and analog functions are controlled by a serial interface. The readout of Saphira allows to read multiple windows, each independently resettable. Glow protection and APD protection circuit are also included.

The Fig. 8 shows the functional bloc diagram of the ME1000 SAPHIRA readout circuit used currently in C-RED. ME1000 is the last version of the Saphira readout circuit. The ME1000 scanning modes include a Read-Reset-Read per row function, so the user can have complete control of the correlated-double-sampling process. Saphira ME1000 incorporates also glow suppression by using 100% metal screening. A reset current limit function has been added in this readout circuit version to protect the array from short circuit APDs.

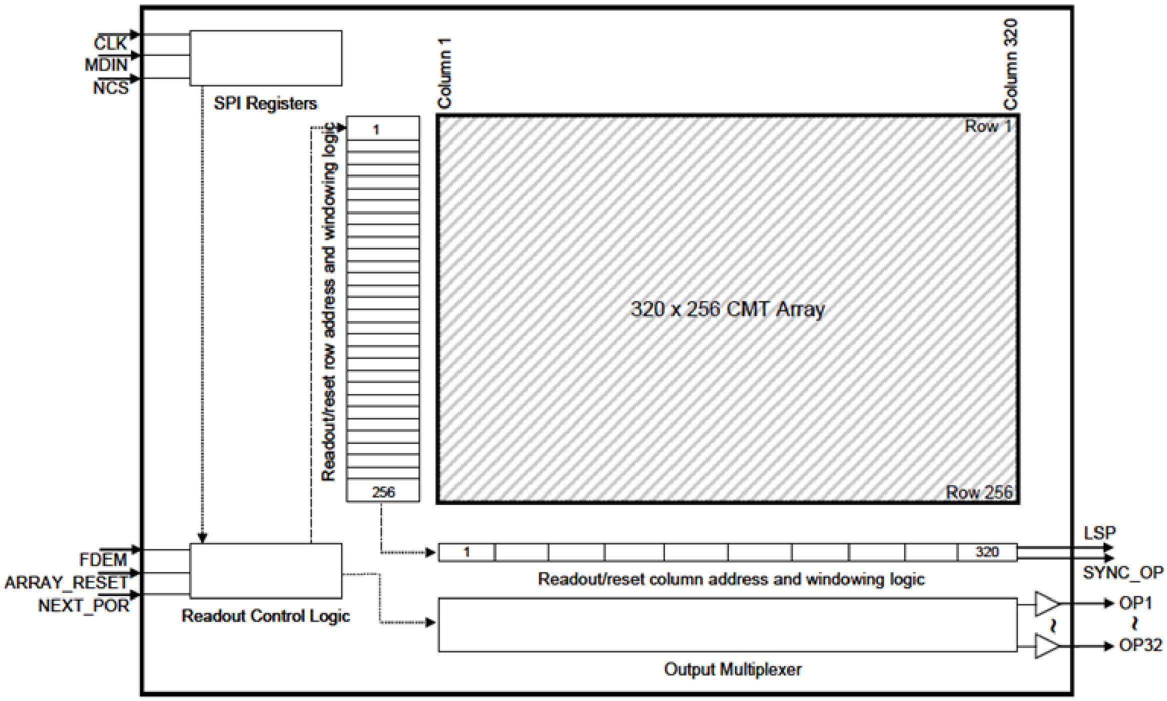

Fig. 8: the SELEX SAPHIRA ME1000 readout circuit architecture.

3.3 The C-RED camera characteristics and performances

The C-RED one camera has the following main characteristics:

- MCT near IR Avalanche Photo Diode 320X256 with Selex Saphira detector.
- Sub-electron readout noise,
- 32 outputs, up to 2000 fps.
- Mean Readout noise at 2000 fps and gain 60 <1 e.
- 70% QE.

- Zynq System on Chip from Xilinx embedded
- Supported readout modes: read-reset-read per row, embedded multiple non destructive readout, rolling reset
- Pulse tube packaging cooling down to 50 K
- Custom design available (beam aperture)
- Cameralink full interface

In addition, the Table 1 below shows the expected performances of the camera:

Test	Result
Mean Dark + RON	<1 e-
Digitization	16 bits
Operating Temperature	80 K
Mean Quantum Efficiency from 1.3 to 2.5 µm	70 %
Operability +/-30 %	99.3 %
Image full well capacity	200 000 e-
Excess noise factor F	1.25

Table 1: expected performances of the C-RED one camera.

3.4 Measured performances

Quantum efficiency

The array quantum efficiency peaks up to near 80% and the array AR coating may be optimized on a per-device basis for J, H or K bands. Fig. 9 shows the effect of this QE optimization. Moreover due to junction heterostructure with 3.5µm cutoff wavelength HgCdTe material for the avalanche multiplication region and 2.5 µm material for the absorber, the device is sensitive in L band at gain 1 but not with APD gain. This is due to photon penetration depth (longer wavelength photons penetrate deeper in the material and therefore are less amplified). We've measured that already with low gains (in the range of 5 to 10), the L band sensitivity is decreased to near zero, leaving only J, H and K sensitivity.

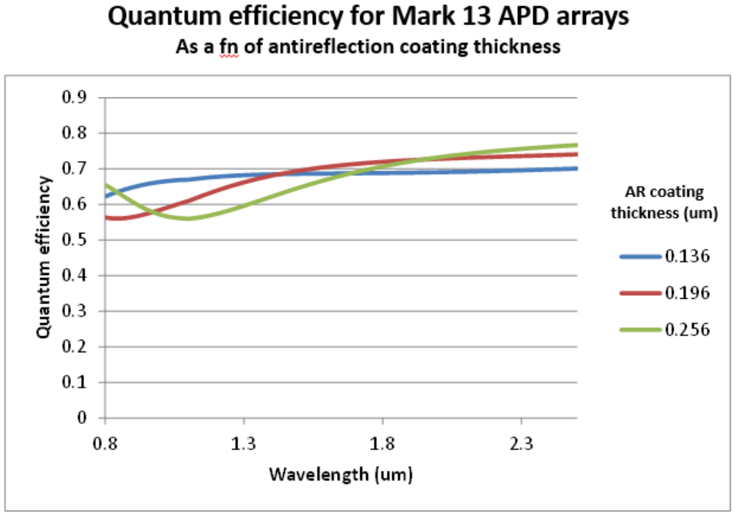

Fig. 9: AR coating and QE optimization for J, H or K bands of Mark13 e-APD diodes.

Multiplication gain

APD gain is measured by illuminating the sensor with a weak light, apply APD gain, and measure the ADU change. To get rid from any FPN, the level measurement is done by subtracting images at 50FPS and 25FPS. Fig. 10 shows that APD gain vs bias voltage and the exponential fit. The gain can be expressed as $G=0.4121e^{0.3548Vbias}$ which is in accordance with other measurements carried out by various groups using these devices.

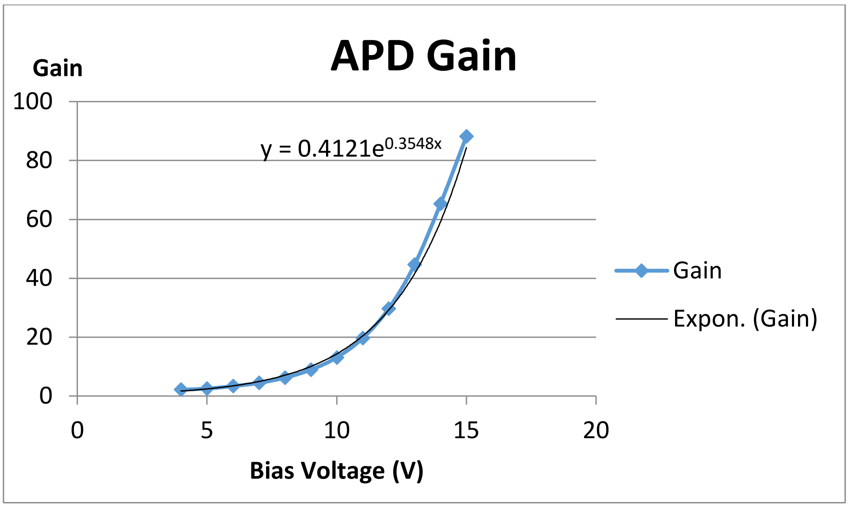

Fig. 10: Measured APD gain vs polarization voltage of MARK 13 array and exponential fit.

Readout noise

The noise measurement is done by measuring the temporal variation of the image, sensor in the dark looking at a 80K blackbody. Measurements have been done for single readout and CDS readout. Taking into account 28fF node capacitance, the KTC noise should be in the range of 35e- at 80K. Fig. 11 shows the sensor readout noise in single readout and CDS readout modes. It can be noticed that the CDS mode reduces the readout noise by the KTC noise at the expense of a supplementary readout, hence a reduction in the maximal frame rate by a factor of two. It might be noticed that the noise scales perfectly with APD gain, therefore increasing APD gain does not increase readout noise as it should be expected. Finally it can be noticed also that for gains > 30, the array enters in subelectron readout whatever is the readout mode (single readout or CDS). This is really a change of paradigm in the way of operating infrared arrays since CDS is no more needed to minimize readout noise.Simply by increasing the APD gain, one can have very low noise operation, without compromise on readout speed, but at the expanse of a lower dynamic range (typically 30% less dynamic range in our case).

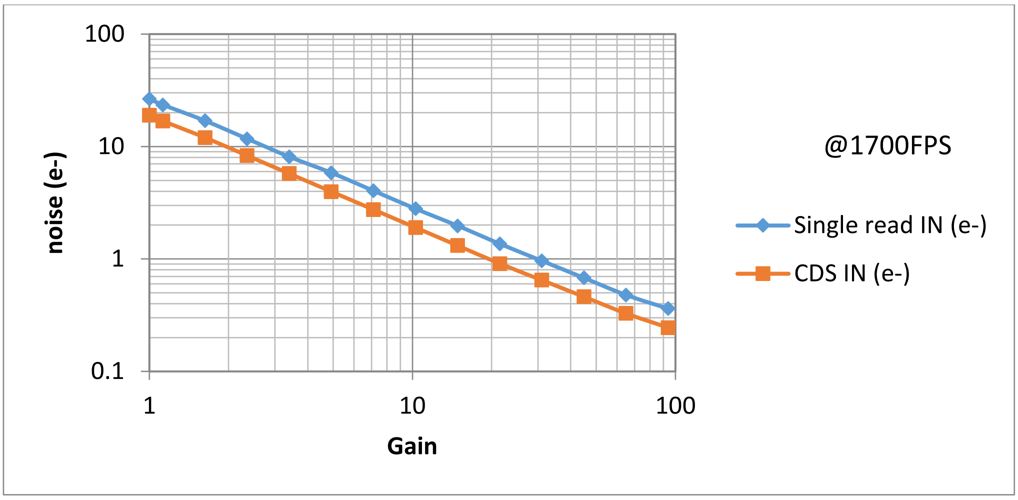

Fig. 11: Measured input referred readout noise vs APD gain for single readout and CDS readout.

Cosmetics

One of the advantage of this sensor is its extremely good cosmetics, even when high gain is applied. Some other groups reported only a few dead pixels over the entire array, which is due to the HgCdTe growing process (MOVPE). Even with our engineering grade device, the cosmetics was excellent only showing a few pixels with leakage dark current (see Fig. 12 that shows images at various gains). Again this device changes the paradigm of infrared FPA use since we have a cosmetics comparable to a CCD, or even better with nearly zero defect. This device is really operated like an EMCCD, and people already familiar with these latter ones will notice almost the same behavior except that unlike EMCCDs, e-APDs are not sensitive to overillumination. The red and grey curves of Fig. 14 perfectly illustrate this common behavior.

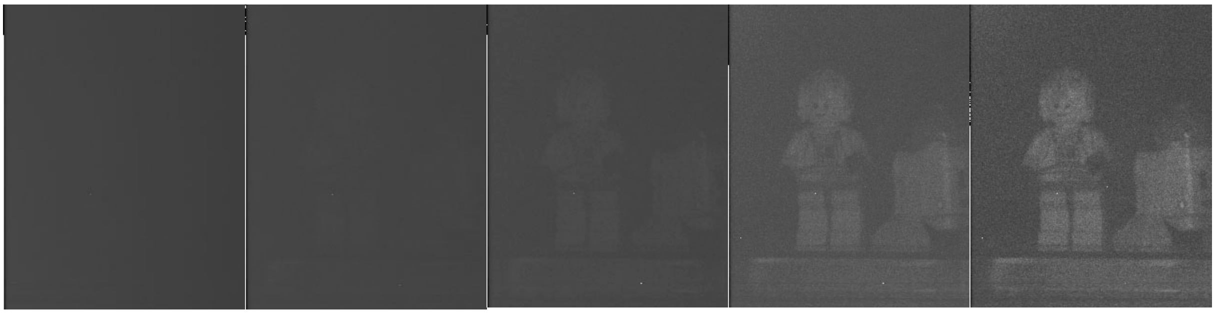

Fig. 12: Low light scene imaged with gains of 1,6,13,45 and 90 (from left to right) showing only a few defective pixels at high gain (<10 defective pixels) on our engineering grade device, CDS readout at 1700 FPS.

4. VISIBLE DETECTORS FOR INTERFEROMETRY

4.1 The EMCCD technology and CCD220

The CCD220 (see Fig. 13) is an L3Vision™ sensor fabricated by e2v technologies and designed for very high frame rate and low signal applications such as wavefront sensing or adaptive optics. The image area is split into two half sections for split frame transfer operation using metal-buttressed electrodes for high speed. The image section can be operated in inverted mode if desired. The device uses eight output amplifier circuits that are capable of operating at an equivalent output noise of less than one electron (rms) at frame rates of >1.2 kHz. All outputs must be used for full image read-out. The e2v technologies back-thinning process ensures high quantum efficiency over a wide range of wavelengths, with a >90% typical peak response.

The device functions by converting photons to charge in the image area during the integration time period, then transferring this charge through one of the image and store sections into the readout register. Following transfer through the readout register, the charge is multiplied in the gain register prior to conversion to a voltage at the output amplifier. The multiplication gain may be varied by adjustment of the multiplication phase clock amplitude RØ2HV. The device is supplied in a sealed integral Peltier package, which provides a nominal operating chip temperature of 233K (-40 °C). A variant of this device is also available with an integral shutter (CCD219).

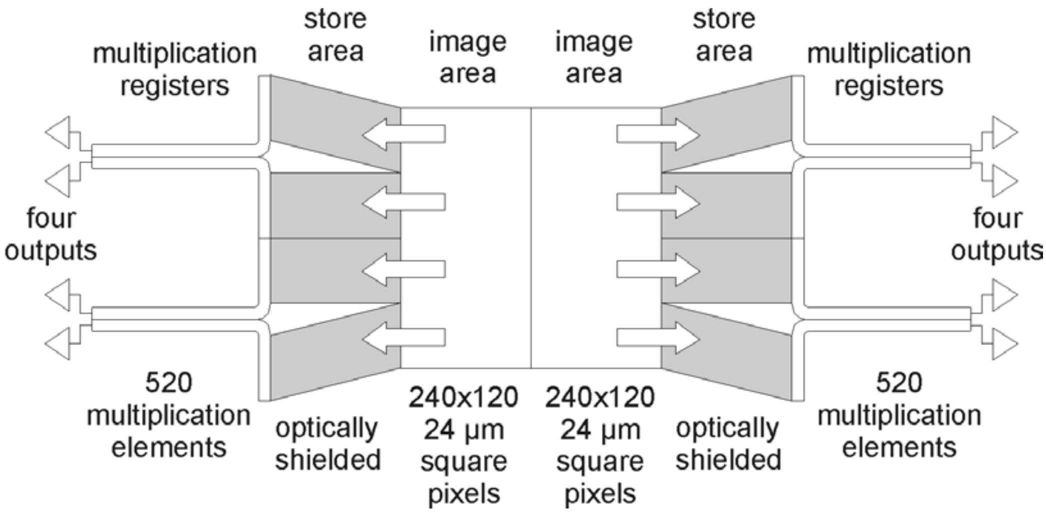

Fig. 13: Schematic of e2v technologies 240x240 pixel L3Vision CCD220. Eight Electron-Multiplying (gain) registers are used to obtain sub-electron noise at frame rates of 1300 fps.

4.2 The OCAM2 camera based on the CCD219/220 EMCCD

OCAM2, the production version of the OCam test camera, is commercialized by First Light Imaging. The OCAM2 system is capable of driving all members of the CCD220/219 family at their nominal speed (1.5kframes/s) and transmitting the data at full speed through a CameraLink interface. The camera controller is able to drive deep depleted variants with multilevel clocking at voltage levels up to 24V with speeds of 10Mlines/s (at a nominal phase load of 1nF). To obtain such a speed, OCAM2 uses a special phase generation scheme. An arbitrary waveform generator is used. The core sequencer feeds a fast 14bit D/A converter running at 109 Mfps followed by a class AB power amplifier that drives the CCD's phase. Using this generation method, it is possible to compensate for the parasitic PCB track/package pin inductance that makes a resonator with the CCD's phase and produce potentially destructive overshoots by using de-emphasis and suitable drive waveforms. This method can also be used to reduce the slew rate of the phase drive in order to minimize the generated Clock Induced Charges (CIC) [8].

The controller handles the 8 L3vision outputs with high voltage clocking up to 50V voltage swing. A big effort has been made to have high voltage stability (less that 1mV/hour of drift) in order to ensure a constant gain over a long period. The system digitizes the CCD signal using correlated double sampling with 14 bits resolution. Standard interfacing of the camera is performed by using a PC computer running Windows OS fitted with a CameraLink full grabber and a proprietary software capable of gathering in real time the extremely high data rate of 220Mbytes/s produced by the camera.

4.3 Use of OCAM2 for visible interferometry in photon counting mode

OCAM2 has been tested in November 2012 at the focus of the VEGA instrument. VEGA is a spectro-interferometer operating in the visible range and installed on the CHARA interferometric array (Mount Wilson Observatory, USA). OCAM2 has been operated with the highest gain (1000) and with frame rates between 50fps and 500fps. We recorded fringes with 2 and 3 telescopes on 10 stars up to m_V=5.5.

Based on this first test, we decided to use OCAM2 as the main detector of the prototype FRIEND. FRIEND is a spectro-interferometer operating in the visible with single mode optical fibers. It is also installed at the focus of the CHARA array. FRIEND is a first step towards a new generation of visible specto-interferometer for CHARA and/or VLTI. FRIEND is operated 2 or 3 times each year since 2014. We record 3 telescopes fringes routinely for stars brighter than m_V=5. In 2017, we plan to use FRIEND with the CHARA AO systems. We expect an important gain in sensitivity (up to mV=9).

Over the past four years, we tested intensively OCAM2 in the context of visible interferometry. We are now able to summarize the main characteristics of the detector required for the next generation of visible spectro-interferometer:

- Frame rate up to 200fps
- QE>90% between 550nm and 850nm
- Low RON (<<1e-) - Uniform over the whole detector
- Low dark current (<0.0002e^-/px/frame) – Cooling temperature down to -80°C
- Low level of CIC (<0.001e^-/px/frame)
- Size: 512x512 pixels

These characteristics should allow a high probability of single photon detection and a low probability of background event detection simultaneously. The size of 512x512 pixels is needed for instruments operating with 4/6 telescopes and spectral resolution R>3000.

5. SIGNAL TO NOISE COMPARISON BETWEEN DETECTOR TECHNOLOGIES

At various illumination levels, the Signal to Noise-Ratio (SNR) of various visible and infrared detectors is computed as:

$$SNR = \frac{S}{N} = \frac{QE * S}{\sqrt{QE * S * F + \sigma^2}}$$

In this equation, the detector is assumed to be fast enough to have negligible dark signal. Here, S is the illumination signal (in photons/pixel/image), QE is the detector quantum efficiency, σ is the readout noise, and F is the excess noise factor. A comparison of infrared detectors shows how much an e-APD sensor can improve the SNR for faint fluxes and also that its sensitivity in the infrared is directly comparable to EMCCDs in the visible—the latter of which are considered to be the most sensitive detectors (see Fig. 14).

Currently, the gain in performance of EMCCDs compared to classical CCDs in the visible is smaller than the gap between C-RED One and its competitors— whether they be slow-scan HgCdTe or even indium-gallium-arsenide (InGaAs)-based cameras. This advance in performance characteristics should allow e-APD imagers to usher in a new era in high-performance infrared detection.

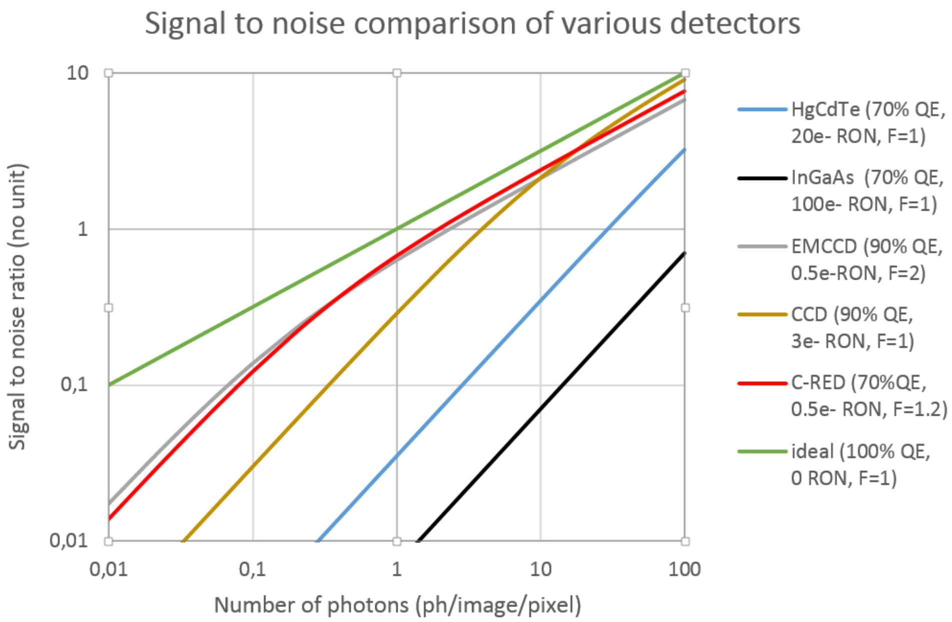

Fig. 14: Signal to Noise comparison of various detector technologies. CCD and EMCCD are sensitive in the visible. They are compared with IR detectors (InGaAs, slow scan HgCdTe and the C-RED e-APD camera).

6. CONCLUSION

In conclusion, the development of new detectors dedicated to fast applications is offering sub-electron readout in the visible and in the infrared, opening a new era in terms of sensitivity to the detectors for interferometry.
This paper illustrates a long term and coordinated fast detectors development in Europe involving cutting edge detectors and camera systems industry associated with ESO, academic French laboratories (LAM and IPAG) and the First Light Imaging spin off. Among these developments, a huge effort has been made on e-APD infrared arrays, together with the parallel development of state of the art camera systems using this disruptive technology.

One of these IR devices is called RAPID and is based on a 1.6 kfps 320x255 pixels infrared APD arrays. This detector is now permanently installed on the ESO VLTI telescopes as focal plane camera for the PIONIER instrument. This is the first time a visible-infrared APD fast detector (1700 fps, 1 e noise) is producing permanent astronomical data on a large world class telescope.

In the meantime, the C-RED 1 infrared camera is offered by First Light Imaging, taking advantage of the 320x256 Selex Saphira e-APD characteristics and performances in its latest and most advanced version. Sub-e noise at 3500 fps has been measured for the first time for an infrared device. This is the best compromise in terms of noise and speed for an infrared camera ever reported in the world.

7. ACKNOWLEDGMENTS

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REFERENCES

[1] Gert Finger, Domingo Alvarez, Derek Ives, Leander Mehrgan, Manfred Meyer, Jörg Stegmeier, “SAPHIRA detector for infrared wavefront sensing”, Proc. SPIE 9148, Adaptive Optics Systems IV, 914817 (August 7, 2014); doi:10.1117/12.2057078.

[2] P. Feautrier et al., “Advances in detector technologies for visible and infrared wavefront sensing”, Proc. SPIE, 8447, 84470Q (Sept. 13,2012).

[3] P. Feautrier et al., “Revolutionary visible and infrared sensor detectors for the most advanced astronomical AO systems”, Proceedings of the SPIE, Volume 9148, id. 914818 16 pp. (2014).

[4] J. Rothman *et al.*, “HgCdTe APDs for space applications”, ICSO 2014 - International Conference on Space Optics, 7 - 10 October 2014, Tenerife, Canary Islands, Spain.

[5] First Light Imaging SAS, http://www.firstlight.fr

[6] S. Derelle et al., “A Monte Carlo study of multiplication and noise in HgCdTe avalanche photodiodes,” Proc. SPIE 7003, 70031P (Apr. 2008).

[7] LeBouquin, J.B.; et al.: "PIONIER: a 4-telescope visitor instrument at VLTI", 2011, A&A, vol. 535, article id 67.

[8] “Low-light technical note 4 dark signal and clock-induced charge in l3vision ccd sensors,” tech. rep., E2V Technologies, http://www.e2vtechnologies.com/secure/datasheets/l3vision_ccds/low_light_tn4.pdf, June 2004.