34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

A 2x2 Array of EMCCD-Based Solid State X-Ray Detectors

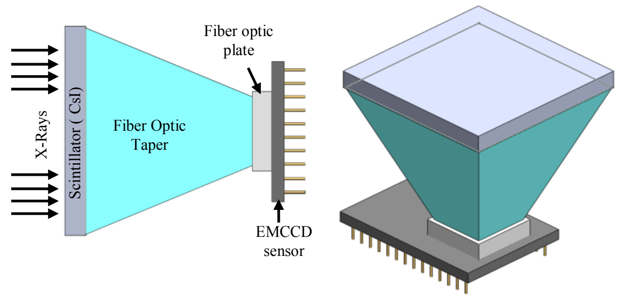
P. Sharma, *Student Member, IEEE* , S.N. Swetadri Vasan, *Student Member, IEEE*, A.H. Titus, *Senior Member, IEEE,* A. N. Cartwright, *Senior Member, IEEE*, D. R Bednarek, S. Rudin, *Life Member, IEEE*

***Abstract*— We have designed and developed a new solid-state x-ray imaging system that consists of a 2x2 array of electron multiplying charge coupled devices (EMCCDs). This system is intended for fluoroscopic and angiographic medical imaging. The key components are the four 1024 x 1024 pixel EMCCDs with a pixel size of 13 x 13 µm^2. Each EMCCD is bonded to a fiber optic plate (FOP), and optically coupled to a 350 µm thick micro-columnar CsI(TI) scintillator via a 3.22:1 fiber optic taper (FOT). The detector provides x-ray images of 9 line pairs/mm resolution at 15 frames/sec and real-time live video at 30 frames/sec with binning at a lower resolution, independent of the electronic gain applied to the EMCCD. The total field of view (FOV) of the array is 8.45 cm x 8.45 cm. The system is designed to also provide the ability to do region-of- interest imaging (ROI) by selectively enabling individual modules of the array.**

I. Introduction

Medical x-ray imaging systems used in fluoroscopic and angiographic neuro-vascular applications demand high resolution, large dynamic range and adequate FOV. Current x-ray imaging systems include x-ray image intensifiers (XII), flat panel detectors (FPD) and charge coupled device (CCD) based detectors. While XII based detectors suffer from problems of veiling glare and image distortion such as pincushion or s-shaped distortions [1] due to the earth's magnetic field, the biggest limitation of both XIIs and FPDs is their limited spatial resolution of approximately 2-3 cycles/mm. A new CCD-light-image-intensifier-based x-ray detector, the Micro-Angiographic Fluoroscope (MAF) [2] being developed by our group at the UB-TSRC, provides exceptional performance in terms of resolution, speed and sensitivity but requires a high voltage above 1000V. Moreover, the MAF has a small FOV which is not extensible.

To overcome these limitations we have designed and developed from the discrete component level a 2x2 array of high resolution EMCCD-based solid state x-ray detectors with large dynamic range suitable for fluoroscopic and angiographic applications. The FOV of the 2x2 array of these detectors is 8.45 cm x 8.45 cm and can be extended to any arbitrary size in both dimensions by adding more modules. This array also allows ROI imaging by selectively enabling individual modules. We have previously demonstrated [3] these properties using a single EMCCD - based prototype solid state x-ray detector. Fig. 1 shows the basic structure of an EMCCD-detector wherein a scintillator (CsI) converts x-rays to light photons which are optically coupled to an EMCCD using a FOP and a FOT. Fig 2 shows an x-ray image of a lead line pair phantom taken at 50 kVp and 1.2 mAs through the prototype detector showing 9 line pairs per mm demonstrating the high resolution capability of the detector.



(a) Side view (b) Isometric view

Fig.1. EMCCD-based X-ray detector

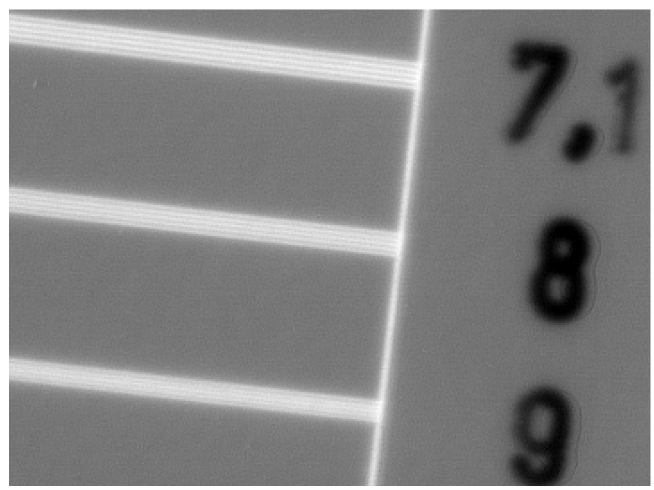


Fig.2. X-ray image of a line pair phantom showing 9 line pairs/mm

II. Design, Construction and Methods

A. Detector

A detailed description of the detector as shown in Fig.1 is given below.

1) *EMCCD sensor:* The core of the detector is a back-illuminated L3 Vision EMCCD sensor (CCD201-20) manufactured by e2v Technologies Ltd, UK [4]. It consists of 1024 x1024 active image pixels each 13 µm x 13µm in size providing an active image area of 13.3 x 13.3 mm^2. As shown in Fig. 3, the EMCCD is similar to a frame-transfer CCD with the addition of a multiplication register stage; this stage requires the application of a voltage of 40-45V to

Manuscript received on March 14, 2012. This work was supported in part by NIH Grants R01-EB008425, R01-EB002873.

P. Sharma, S.N. Swetadri Vasan, A.H Titus, A. N. Cartwright, D. R. Bednarek and S. Rudin are with the Electrical Engineering Department and Toshiba Stroke Research Center at University at Buffalo, The State University of New York, Buffalo, NY 14260-1920, USA (The corresponding author is P. Sharma, phone: 716-829-5417; e-mail: psharma4@buffalo.edu).

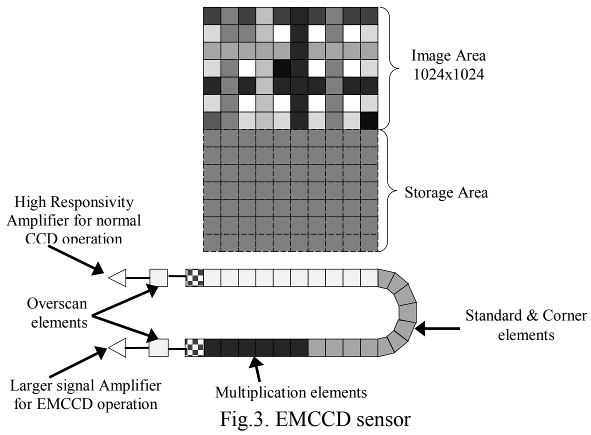


Fig.3. EMCCD sensor

cause avalanche multiplication of electrons through impact ionization. The probability of impact ionization or gain per stage is given by g providing a total gain of $M = g^N$ where N is the number of gain stages. Since the signal amplification happens during the charge-to-voltage conversion process in the output amplifier (this being the main source of readout noise), the effective signal is increased well above the noise floor. Since the EMCCD is a back-illuminated sensor, it has a quantum efficiency of over 92% for wavelengths ranging from 500 to 600 nm.

2) Scintillator: A 350 µm thick structured cesium iodide CsI (T1) scintillator is used to convert the incoming x-ray photons into light photons. CsI (T1) has an effective atomic number of 54 resulting in good quantum detection efficiency over the medical x-ray energy range (20-140 kV). The emission spectrum response of CsI ranges from 350 to 700 nm with a peak near 565 nm [5] which matches well with the response of the EMCCD sensor.

3) Fiber Optic Tapers & Plates: The fiber optic plates (FOP) and a fiber optic taper (FOT) (Incom, Inc., Charlton, MA) are used to channel the light photons from the scintillator onto the EMCCD. A custom FOP [6] of dimension (15x15x5) mm is bonded using epoxy on the imaging region of the EMCCD. A special fused FOT array (Fig. 4) was used for the 2x2 array of the detectors wherein four identical FOT's with a magnification ratio of 3.22:1 are fused together and optically coupled to the FOP and the scintillator, providing an effective pixel size of 41.86 x 41.86 µm^2 (3.2 times the pixel size of EMCCD) and a total FOV of 8.45 cm x 8.45 cm.

B. Electronics

The control and readout electronics for the detector are constructed using discrete components and consist of the following major components:

1) Driver board: Driver board is a six layer PCB board and converts the input signals (0 to 3.3V) from FPGA into different voltage swings as required by EMCCD. Four digital Isolators chips IL260 from NVE Corp., Eden Prairie, MN [7] are used to separate digital and analog planes. For image/storage area signals eight EL7158 chips from Intersil Corp., Milpitas, CA [8] are used per driver board to provide (+7V to -5V) swing at 1MHz. For readout signals four

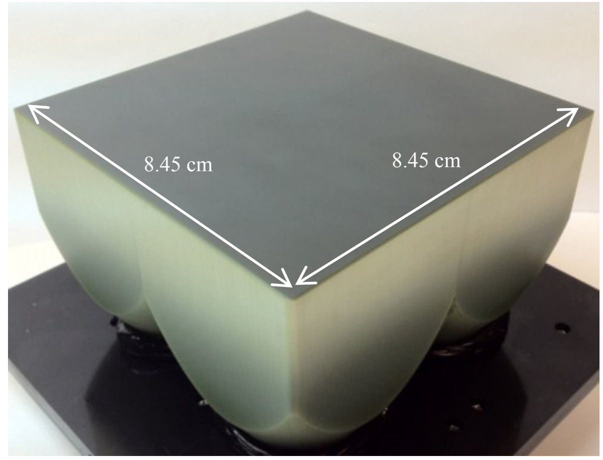
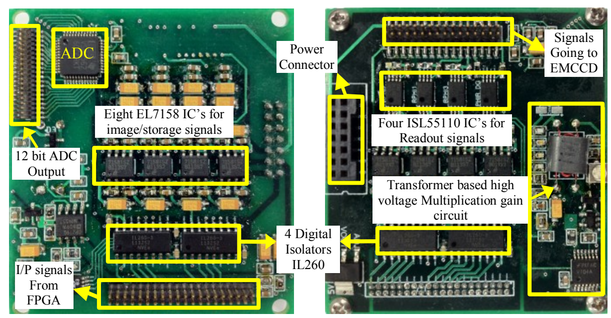


Fig.4. Fused FOT array for a 2x2 array system

ISL55110 chips from Intersil [9] are used per driver board to provide (+12V) swing at 17.5MHz. On-board 12-bit CCD signal processor (VSP2562, Texas Instruments, Inc., Dallas, TX), is used to convert the EMCCD analog output into a 12



(a) Bottom View (b) Top View

Fig.5. Bottom and Top view of the Driver board

bit digital output. A transformer based high voltage gain circuit is used to provide multiplication gain. Fig. 5 shows top and bottom views of the driver board. Four driver boards are used for a 2x2 array.

2) Headboard: The headboard is a 4 layer PCB board that holds one EMCCD and is connected to a driver board using flex cables. Four headboards are needed for the 2x2

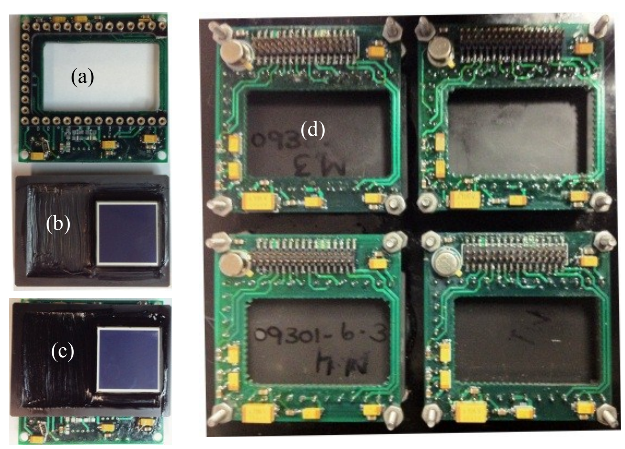


Fig.6. (a) Headboard (b) EMCCD (c) Headboard with EMCCD (d) 2x2 array of headboards with their EMCCDs

array. Fig. 6 shows the headboard by itself, with an EMCCD, and a 2x2 array configuration of the headboards.

Each headboard also has an opening to facilitate attaching a peltier cooler to the EMCCD sensor.

3) FPGA board: A single 4-layer FPGA board supports the XC3S500E-PQ208 (Xilinx, Inc., San Jose, CA) that generates clocks for each of the individual modules programmed using Verilog HDL. A 280 MHz crystal oscillator of is used to generate the master clock; this frequency allows for 3.57 ns adjustments of delays in the various clocks to the components which is needed to optimize the output from the EMCCD. Fig. 7 shows the FPGA board. Each module has two connectors, the larger connector feeds signals from FPGA to driver board, while smaller connector feeds the 12 bit data from driver board to FPGA board.

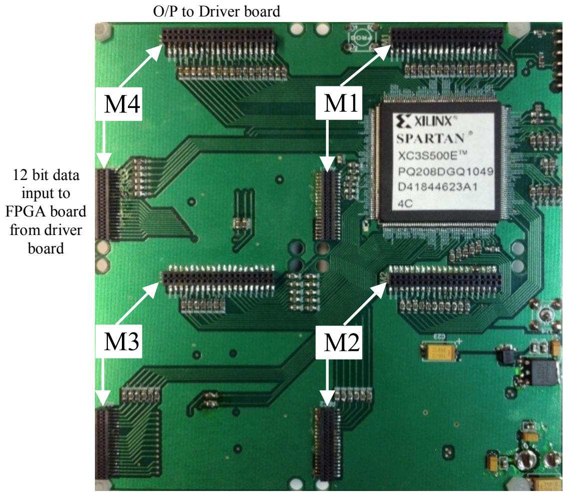


Fig.7. FPGA board

4) POWER board: A single 4-layer PCB power board is used to provide power to the complete 2x2 array system. The voltages for each of the EMCCD sensors can be individually controlled using on-board variable resistors. Fig. 8 shows the power board.

5) Camera Link boards: Two camera link boards (Fig. 8) are used to send the 12 bit data from each EMCCD to the processing computer over a CameraLink cable. Each board is a 4-layer PCB board and can simultaneously handle data from two EMCCDs.

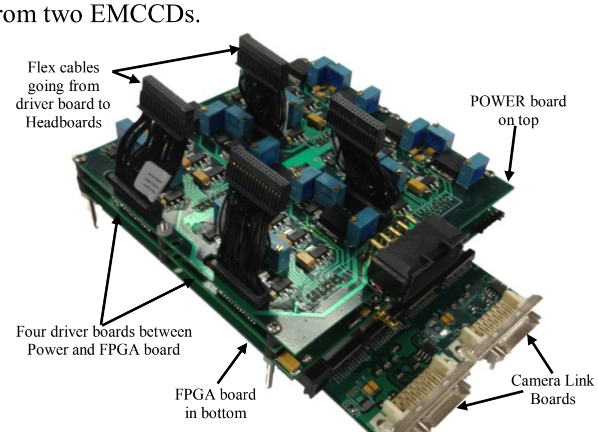


Fig.8. Complete electronic assembly for the 2x2 array

Fig. 8 shows the complete electronic assembly of the power board, FPGA board, CameraLink boards and the four driver boards. The driver boards are sandwiched between the power board at the top and the FPGA board in the bottom. The flex cables coming from each driver board connect to their respective headboards and EMCCDs. Fig. 9 shows the complete system with fused 2x2 FOT array connected to EMCCDs on their headboards which are connected to other boards using flex cables.


Fig.9 Complete system assembly for the 2x2 array

C. Data Acquisition:

For acquiring the 12 bit digital output a CameraLink image acquisition board (NI PCIe-1430 from National Instruments, Inc) is used. The CameraLink standard provides a fast interface for high resolution and high speed cameras with data rate capabilities up to 2 Gbit/s. The software platform LabVIEW (National Instruments, Austin, TX) is used to control the camera as well as acquire and process the images. Fig. 10 shows the data acquisition scheme wherein an x-ray trigger from Toshiba x-ray machine goes to the prototype detector. At every trigger, the detector acquires x-ray images which are sent to the processing computer through CameraLink cable. The experimental setup used to test the prototype detector is shown in fig 11. The CsI (T1)

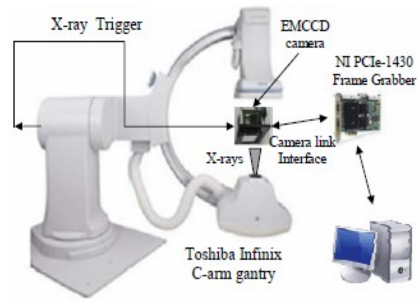


Fig.10. Data acquisition scheme for the prototype detector

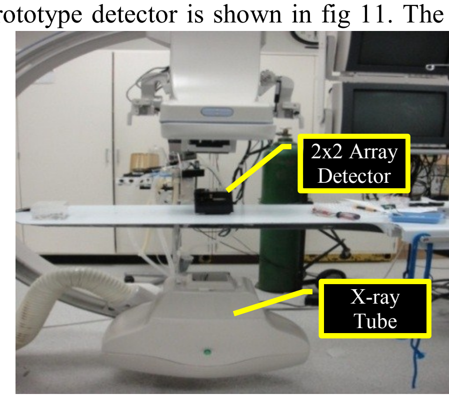


Fig.11. Experimental setup for the detector

scintillator used for the tests is 5 cm x 5cm in area and is placed in the middle of the 2x2 fused FOT array covering approximately one fourth of the total view of each EMCCD.

III. Results & Discussion

X-ray images of a number of test objects are presented below. Fig.12 shows an x-ray image of four different stents taken in real time using the 2x2 array. Each stent was physically placed so that it comes in the FOV of one of the modules. Four types of stents were used: (a) A stainless steel 100 µm strut, coronary stent; (b) A 100 µm strut, nitinol stent; (c) A 60 µm strut, enterprise stent; and (d) A 80 µm strut nitinol stent. As depicted we can easily visualize the individual struts in each of the stents. The technique

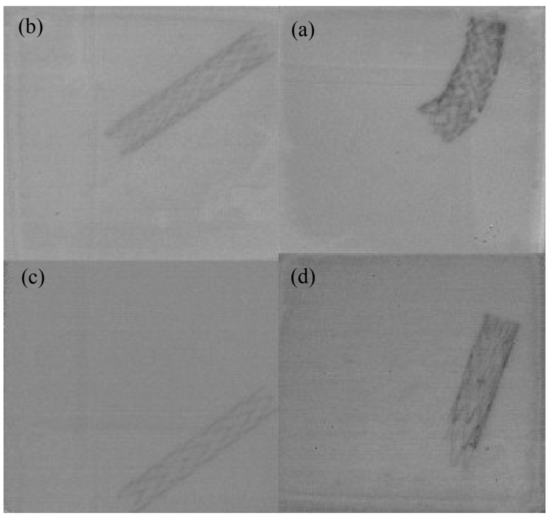


Fig.12. X-ray image of neurovascular stents taken with the 2x2 array

parameters for the x-ray machine were 76kVp, 100mA and 10 ms with standard RQA5 filtration in the beam. Fig.13 shows an x-ray image of a simulated artery block phantom by Nuclear Associates (Fluke Biomedical), Stenosis/Aneurysm Artery block 76-705 taken with the 2x2

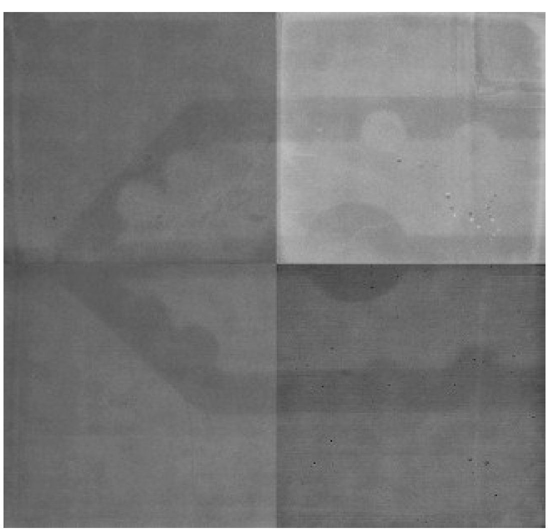


Fig.13. X-ray image of artery aneurysm phantom taken with the 2x2 array

array. The phantom is an acrylic block containing iodine filled simulated arteries. The technique parameters for the x-ray machine were 76kVp, 50mA and 10 ms. Fig.14 shows the image of a line pair phantom with two different EMCCD gains.

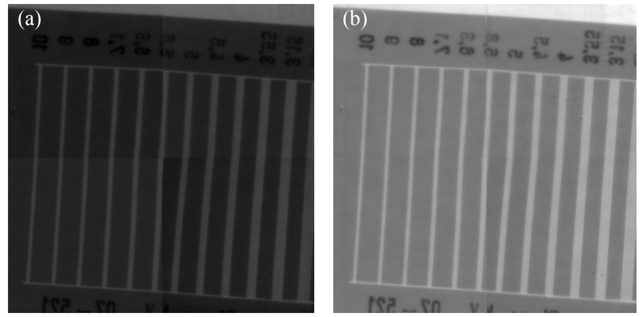


Fig.14. X-ray image of Line Pair phantom (a) Lower gain (b) Higher Gain

It is to be noted that each EMCCD provides different multiplication gains at same input gain voltage due to inherent PVT variations. This results in different luminosities in images from different sensors at same voltage as can be seen in Fig. 12 and Fig. 13. Similar luminosities can be achieved at the hardware level by adjusting the gain voltage for each EMCCD to provide the same digital numbers or at the software level not described here since it is beyond the scope of this paper.

Conclusion

In this paper we have presented a 2x2 array of EMCCD based detectors demonstrating high resolution, large field of view (8.45cm x 8.45cm) with flexibility to extend arbitrarily in two dimensions to increase FOV, capability to do ROI imaging by selectively enabling any of the modules, and variable electronic gain allowing the detector to be operated over large x-ray exposure ranges suitable for both fluoroscopic and angiographic neurovascular applications.

Acknowledgment

This work is supported in part by NIH Grants R01-EB008425 and R01-EB002873, and an equipment grant from Toshiba Medical Systems Corp.
We also thank e2v Technologies Ltd, UK for providing us with technical assistance and EMCCD sensors.

References

[1] S. Rudin, D.R Bednarek, R. Wong, “Accurate characterization of image intensifier distortion”. *Med Phys*. 1991; 18(6):1145-1151.
[2] S. Rudin, Y. Wu, I.S. Kyprianou, C. N. Ionita, Zhou Wang, A. Ganguly and D.R. Bednarek, “Micro-angiographic detector with fluoroscopic capability”, Proc. SPIE 4682, 344 (2002)
[3] Sharma, P.; Vasan, S.N.S.; Jain, A.; Panse, A.; Titus, A.H.; Cartwright, A.N.; Bednarek, D.R.; Rudin, S.; , "EMCCD-based high resolution dynamic x-ray detector for neurovascular interventions," *EMBC, 2011 Annual International Conference of the IEEE* , vol., no., pp.7787-7790, Aug. 30 2011-Sept. 3 2011
[4] www.e2v.com
[5] “FOS - Fiber Optic Plate with Scintillator for Digital X-ray Imaging,” Hamamatsu Corp., Bridgewater, NJ (1996).
[6] www.incomusa.com
[7] http://www.nve.com/Downloads/il260-1.pdf
[8] http://www.intersil.com/content/dam/Intersil/documents/fn73/fn7349.pdf
[9] http://www.intersil.com/content/dam/Intersil/documents/fn62/fn6228.pdf