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A Large Area Detector for X-Ray Applications

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Abstract

A large area detector for x-ray synchrotron applications has been developed. The front end of this device consist of a scintillator coupled to a fiber-optic taper. The fiber-optic taper is comprised of 4 smaller (70 mm x 70 mm) tapers fused together in a square matrix giving an active area of 140 mm x 140 mm. Each taper has a demagnification of 5.5 resulting in four small ends that are 12 mm diagonally across. The small ends of each taper are coupled to four microchannel-plate-based image intensifiers. The output from each image intensifier is focused onto a Charge Coupled Device (CCD) detector. The four CCDs are read out in parallel and are independently controlled. The image intensifiers also act as fast (20 ns) electronic shutters. The system is capable of displaying images in real time. Additionally, with independent control on the readout of each row of data from the CCD, the system is capable of performing high speed imaging through novel readout manipulation.

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Introduction

We have reported on the status of synchrotron radiation sources and detector development in a recent publication [1]. Since then, a survey conducted by Daresbury Laboratory [2] on detectors has concluded that over 50% of the respondents cited a lack of research on detectors as a major technical limiting factor. Currently several third-generation synchrotron sources such as the European Synchrotron Radiation Facility (ESRF) and the Advanced *Light Source* (ALS) are operational and undergoing diagnostic testing. Within the next few years, the Advanced Photon Source (APS) and Super Photon Ring (SPring) will be operational. Although each of these synchrotron x-ray sources costs several hundred million dollars to build and their optium use can only be realized with detectors that can exploit the unique characteristics of these machines, an insignificant percentage of the cost of each machine has gone into detector research. At this time, there are no detectors that fully exploit these machines. There are several reasons why funding of detector development has been outpaced by source developments. Perhaps the most important reason is that while one source can often satisfy a large number of researchers, the detector requirements for the user community are considerably more varied and often suited to a specific type of experiment. Hence, in the past, a majority of the responsibilities of detector development has landed in the lap of the individual experimenters.

However this may not be feasible in the future, considering the money and time necessary to develop state-of-the-art detectors that can take full advantage of the unique properites of the third generation sources. For instance, a study conducted by Sol Gruner (Princeton University) and Brian Rodricks (APS) concluded that the cost for the development of a Pixel Array Device (PAD) chip would be over a million dollars and would take three years to complete. With a comparable amount of money required to develop the associated electronics, the R&D project is probably out of reach for an individual research group. This sort of development project requires not only input from physicists on detector characteristics but also the expertise of electronics engineers, programmers, and chip manufacturers. Therefore, significant detector developments in the future may be only feasible by either large consortiums of users with similar requirements and/or by the synchrotron radiation facilities themselves. In the interim, the most cost effective approach to improved detector design, although often with a loss in optimal performance, is to capitalize on existing technologies. This paper describes such an endeavor.

Charge Coupled Devices (CCDs) have demonstrated their usefulness in a number of fields [3,4,5,6]. Their limitations have been due to their susceptibility to radiation damage as well as inherent slow readout that limits the speed at which a time-resolved experiment can be performed. The speed limitation is especially crucial for experiments in structural biology and protein crystallography in which the samples begin to deteriorate under high radiation exposure. Still CCDs are the detectors of choice for research where two-dimensional information is crucial. CCDs also suffer from being too small. The typical device has 512x512 pixels with each pixel being about 20 microns square. Larger area devices are available (1024x1024 and bigger). These devices do not ultimately give one a significantly larger area, but they do give one a lot of data for analysis. Ideally one would like a device with larger pixels as opposed to a larger number of pixels. One way around this problem has been to use a fiber-optic taper coupled to a CCD [7,8]. This has resulted in a large area (typically 50 mm to 100 mm in diameter) that does not have the radiation damage problems associated with direct x-ray imaging devices. The design of such a device is limited to the largest fiber-optic taper currently available. There are limitations to this method, but with a lack of research in large area x-ray detectors, this is not an unreasonable approach.

Four CCD Fiber-Optic Coupled Detector

With the limitations in current x-ray area detector technology in mind, we have developed a detector that uses four CCDs coupled to a fiber-optic taper to build a large-area detector. Figure 1 is a schematic drawing of the four CCD based detector. This device consist of the following components that are described separately.

1) Fiber-Optic Face Plate: This is a 140 mm x 140 mm x 2.5 mm fibre-optic face plate that couples to the taper. This device has 25-μm pixels with statistical Extra Mural Absorber (EMA) and a numerical aperture of 0.85. For an optical device like this to work, one needs to convert the x-ray photons into optical photons that can be transmitted down the taper. Currently used converters are phosphorous materials that are optimized for the energy of interest. Depending upon whether one wants efficiency or speed (many high efficiency phosphors have a long decay tail, which makes them unacceptable for high speed applications), there are many commercially available phosphors. Also being investigated are single crystals of cadmium tungstate which is a good scintillator. Currently we are using a film of Ga:O:S on the face-plate. Because the fiber-optic taper is extremely fragile,

one does not want to to be in the position of experimenting with different converters directly on it. The fibre-optic face plate is a convenient way of using different phosphors without the possibility of damaging the more expensive and delicate taper.

2) Fiber-Optic Taper: This consist of four individual taper bundles. Each bundle is 70 mm x 70 mm on the large end and 12 mm x 12 mm on the small end. Individual fibres on the large end are 25 microns in diameter surrounded with 6% EMA which minimizes cross talk between fibers and, hence, enhance contrast at the expense of light transmission. The four tapers are epoxied together and polished to better than 10 fringes. The optical center of each taper is held to less than 1mm. The four tapers together give an active area of 140 mm x 140 mm with 25 μm of dead space where they are epoxied. The center-to-center spacing on each taper is 70 mm. The taper system is potted into an aluminum frame to enhance its stability. For a lambartian source of light, this device has a transmission efficiency of 12%.

3) Image Intensifiers: Having a 5.5:1 demagnification in the taper gives us an opening angle of 12 degrees. This results in a loss in light collection efficiency. Because typical light collection from a phosphor is in the 1-10% range, this entire system is very inefficient. To compensate, each small end of the taper is coupled to an 18-mm-diameter microchannel-plate (MCP) based image intensifier. Each intensifier has a fiber-optic input window and a P20 phosphor output window. The resolution on the MCP is 30 lines/mm. Each intensifier has its own power supply and just needs a 2.7-Volt input to turn it off and on. This input is supplied by the control electronics during integration, as a result of

which, the image intensifier also acts as a fast electronic shutter. The device is gateable to 20 ns.

4) Lens System: The output from the image intensifier is focused onto the CCD by means of a 50 mm f1.8 Nikon lens. Because the active area on the CCD (8 mm x 11 mm) is smaller than the output of the taper/image intensifier system (12 mm x 12 mm), the image is demagnified to fit onto the CCD. This is accomplished by the use of a spacer between the lens and CCD.

5) Detector Vacuum Chamber: The four CCDs are coupled to the cold side of Peltier coolers by means of a copper block. The vacuum chamber vacuum is maintained at 1×10^{-2} torr vacuum to minimize condensation on the surface of the CCD. Further, constant temperature water flows through the base of the vacuum chamber to act as a heat sink for the hot surface of the peltier cooler. Thermocouples can be connected to the CCDs and the readings can be used by the temperature controllers to maintain them at a constant temperature. Individual read out control lines go to each CCD.

Figure 2 is a photograph of the detector. Note the inch scale attached to the lab jack onto which the fiber-optic taper is attached.

Detector Control Electronics and Image Display

The CCDs currently used are the TI4849 virtual-phase devices from Texas Instruments. These devices, because of their asymmetric ion implant, require only three waveform to read them out. Each device consists of 584 rows and 390 columns. Each pixel is 22.4 μm square. The image transfer waveform shifts the entire array down one row, thereby moving the last row into the serial readout. Each serial readout waveform moves one pixel off the device. The reset waveform resets the on-chip amplifier. Hence, each image transfer waveform is followed by 390 serial and reset waveforms. It takes 584 image transfers to readout an entire device.

Figure 3 is a schematic of the electronics necessary to control this device. The electronics is an expanded version of a system described previously [9]. They consist of a crate of CAMAC modules controlled by a local resident microprocessor. The microprocessor interprets the commands it receives in the form of encoded binary interrupts, which it then executes. The commands may be the read out of the array, an image display on the color monitor, a column profile of the image, etc. The heart of the electronics are the four sets of independent parallel readout modules for the four CCDs. Because all CCDs, especially experimental devices, do not behave exactly the same way, we are in a position to fine tune the amplitudes that are supplied to the four devices. In this way, we can optimize the performance of each device independently. All four devices are read out in parallel, amplified by a factor of between 50 to 100 , then digitized by a 12 bit digitizer and stored in local RAM memory. Depending on what is required, the data can be displayed on the color monitor and/or stored on the hard disk that is on the MicroVax computer. The local RAM memory is eight mega array in length. This enables us to store eight frames of data at high speed before the memory has to be read out to a hard disk. A synchronized clock defines the waveform generated by the waveform generator. A typical sequence of operation is the fast clearing of the device followed by a predefined integration time followed by a read out of all devices to RAM. The intergration time can be changed on the fly. Further, the local processor supplies the signal that is used to turn on the image intensifiers during the integration period. Hence, the intensifiers also act as fast electronic shutters.

On the CAMAC crate is a local processor to which machine language programs can be downloaded from the MicroVax. This processor talks across Q-bus to another CAMAC module that is capable of displaying high resolution images. The display driver has an advanced CRT controller and a 24-bit color chip. This driver is capable of displaying 256 simultaneous colors out of a pallette of 16 million. The software allows us to vary the sensitivity and offset on the colors down to one bit. Besides displaying bit maps of the image, we can also display column and row slices through the entire image. Capabilites for zoom and pan also exist. The system does not replace a workstation-based imaging software package but is very crucial for diagnostics during the setup of an experiment. Once everthing is setup, the display part of the controller is usually turned off.

Results and Discussion

Visible light testing was done using a fixed masked of size 140 mm x 140 mm. The resolution obtained was two pixels which corresponds to about 150 μm [10]. The CCD and electronics used are similar to one used in the past [9], and hence the behavior of the individual devices should be similar.

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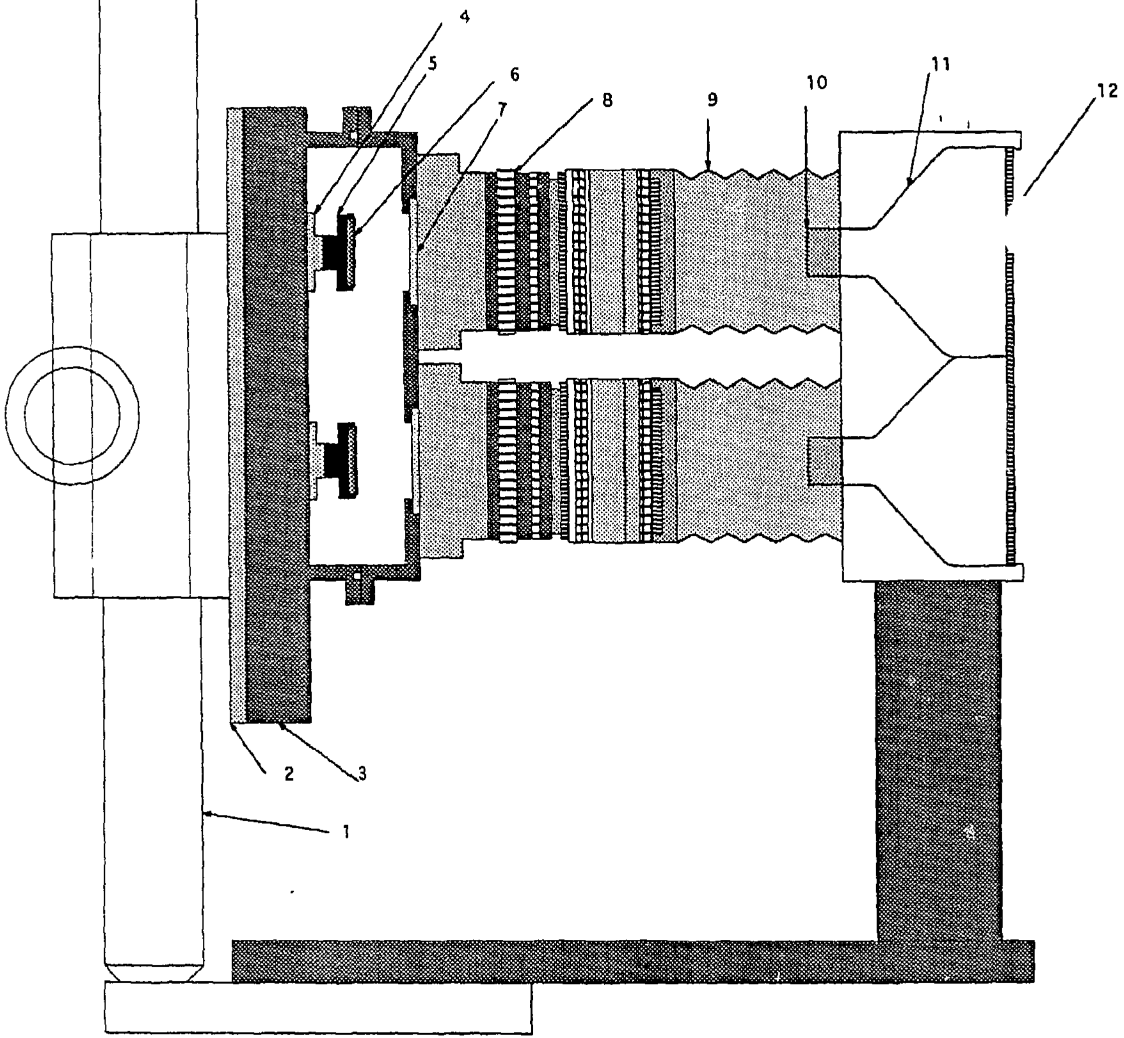
Figure Captions

Fig. 1 Drawing of the various components of the 4 CCD detector.

Fig 2 Photograph of the " Four Shooter ".

Fig. 3 Schematics drwaing of the elctronics necessary to control the device.



1: Newport Optical stand
2: Insulating G10
3:Water cooled vacuum chamber
4: Peltier Cooler
5: Copper conductor
6: CCD
7: Optical window
8: Optical len system
9: Bellows
10: Image intesifier
11: Quad fiber-optic taper
12: Fiber-optics faceplate

FIG 1

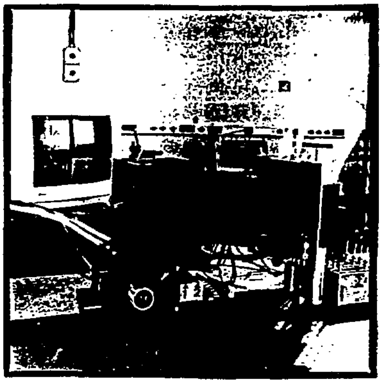
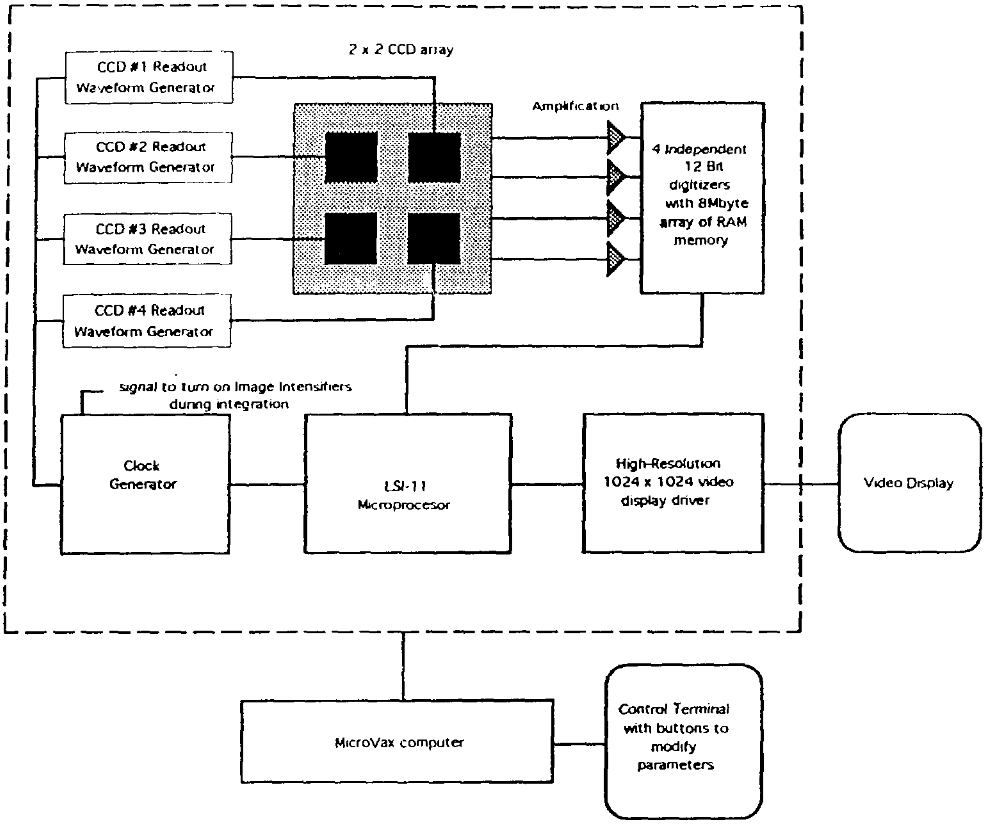


Fig. 2



Specifications:
1: Active Area 140 x 140 mm
2: **Readout time:** 1 sec (normal readout) can store upto 8 frames in 4 secs
Can also do mulitple exposures with a 100μsec time-resolution
3: **Spatial Resolution:** 150 μmts
4: **Fiber-taper:** 5.5:1 reduction with 25μ fibers on large end
5: **Face-plate:** 1:1 with 8μ fibers
6: **Image Intensifier:** DEP 18mm with 30μ resolution and a gain of 10000
7: **Lenses:** Nikon 50mm f1.8
8: **CCDs** : TI virtual phase devices (384 x 590) with 22.4 μ pixels
9: **Peltier Cooler:** Two stage with a 91 degree temperature gradient

Fig 3