A Novel Detection System Consisting of a Large Area Sensor and a Multi-Cell Si-Pad Array Operated in Spectroscopic Mode for X-Ray Breast Imaging

D. G. Darambara, Member, IEEE, P. J. Sellin, Member, IEEE, G. Maehlum

Abstract—The ability of coherent x-ray scatter to provide the molecular structure of breast tissues could add a new dimension in x-ray breast imaging capable of tracking the molecular structural changes during disease progression and of improving the sensitivity to low-contrast lesions without increasing the radiation dose. Work is under way to build a laboratory prototype dual-sensor breast-imaging scanning system, which combines the diagnostic information from both the transmitted primary and the forward scattered x-rays. This required the design and development of a coherent x-ray scatter detection system based on a high-resistivity multi-element 2D Si-pad array, a multi-channel low-noise pulse processing front-end electronics chip, the XA1.3, and a new DAQ system. Results on the characterization and optimization of the detector-readout electronics-DAQ system and its performance to measure diffraction signatures are presented.

I. INTRODUCTION

DPESTIVE significant advances, the major challenge in diagnostic x-ray imaging remains the determination of small size lesions in a low-contrast environment, while keeping the dose applied as low as possible. The screening situation in the diagnosis of breast cancer has not changed appreciably, and x-ray mammography remains the gold standard for screening, although its specificity is ∼15-20%. The subject of this research work is to develop an alternative approach that allows the spatial distribution of x-ray scattering properties to be mapped throughout the interior of the tissues concerned. In medical x-ray imaging the coherent x-ray scatter makes up a considerable fraction of the total x-ray scattering process and peaks at precisely those energies where x-ray breast imaging is performed [1], [2]. The low-angle (≤ 10°) behaviour of coherent scatter is highly dependent on the chemical and structural properties of the scatterer. Its intensity, as a function of angle, is related to the molecular structure of the object being irradiated. Every molecular structure has its own signature scattering pattern. The origin of the peaks in the patterns is the interference of photons scattered from the molecules of the medium. These interferences produce one or more peaks in intensity close to the forward direction and the complete distribution is considered as characteristic of the investigated sample. Many biological tissues have significant spatial ordering and readily diffract x-rays. X-ray diffraction measurements on biological materials [3]-[9] showed that the molecular structure of diseased tissues undergoes significant changes, and hence, the structure can be understood as a fingerprint of the disease. In particular the x-ray coherent scatter cross-sections of breast tissues are shown to be quite distinctive and different, in a material-specific way, for specific scattering angles and photon energies. The ability of coherent x-ray scatter to provide the molecular structure of breast tissues could add a new dimension in x-ray breast imaging capable of tracking the molecular structural changes during disease progression and of improving the sensitivity to low-contrast lesions without increasing the radiation dose.

The important parameters in the design consideration of x-ray imaging systems to clearly identify tissues of interest from other tissues surrounding them, and hence, to enhance the image contrast, are: the incident photon energy-scatter angle, the scatter intensity-tissue volume and the diffraction sensitivity-spatial resolution. By carefully incorporating these design specifications, work is under way to build a laboratory prototype dual-sensor breast-imaging scanning system [10], which combines the diagnostic information from the conventional x-ray transmission with that from the low-angle x-ray scattering. Fig. 1 shows the experimental set-up for simultaneous measurements of the transmitted primary and the forward scattered x-rays. In particular, the coherent x-ray scatter detection system required the design and development
of a high-resistivity multi-element 2D Si-pad array with a multi-channel low-noise pulse processing front-end electronics chip and a new DAQ system. Results regarding the characterization and optimization of the detector-readout electronics-DAQ system and its performance to measure diffraction signatures of most commonly used standard materials of interest are presented here.

II. COHERENT X-RAY SCATTER DETECTION SYSTEM AND ITS ELECTRONICS

The Si-pad detectors are sufficiently quantum efficient and operate in spectroscopic pulse-counting mode. These detectors developed in collaboration with Sintef were optimised to measure x-ray photons in the energy range of 12-45 keV, with a FWHM energy resolution of about 1-3 keV. Each detector module consists of an array of 6x21 pad detectors aligned on a 2 mm pitch with a 12mm x 42mm of active area. The size of the active electrode of each pad is typically 1.8mm x 1.8mm. Each detector module consists of a DC-coupled single sided device fabricated from high resistivity 1 mm thick silicon. A multi guard ring structure was incorporated around the edge of each detector module to allow stable operation in full depletion, corresponding to operation bias voltages, \( V_{bias} \), of 150-300 V. Thin metal traces from each detector pad lead to bond pads located on one side of the detector suitable for direct wire bonding to a PCB mother-board containing the XA1.3, a high-density IDE readout chip.

The XA1.3 is a 128-channel pulse counting custom-tailored ASIC. It is a low-noise, low-power, self-triggered and data driven charge signal acquisition chip, which upon a signal detection above the adjustable threshold responds with sending out the energy- and position-information of the hit channel. If the amplitude of the peak analogue signal is larger than the external adjustable threshold voltage, \( V_{th} \), a trigger signal is generated internally and the trigger plus the channel address are shown as analogue current outputs. Each detector module consists of an FR4 support card with a high-density 26-pin flat cable connector to the external DAQ circuit.

The DAQ system consists of a programmable gate array to control the data acquired from three 12-bit A/D converters, which are clocked continuously. When a strobe pulse occurs, the relevant simultaneous samples from the converters are packed into a 5-byte data package and clocked into a FIFO. The FIFO output transmits data to a PC data acquisition card, NI PCI 6534 buffered digital I/O card. A menu-driven DAQ software runs the whole detector-electronics system. All the configuration parameters, e.g. the threshold voltage \( V_{th} \), are set through this software. The DAQ software operates either in a calibration or a normal mode. Before it can be used to acquire data (normal mode), the software needs to calibrate the detector and the ADC channels (calibration mode). This involves acquiring data for decoding the detector address from ADC channels B and C and the signal strength data from ADC channel A for 3 different calibration signal strengths. Once the calibration has been done, one can switch to normal mode, where data is acquired and automatically decoded. Gain shift correction and energy conversion in keV are also implemented. The visualisation of the data –in raw ADC values and/or Energy in keV- is implemented through a LabView-based programme (single channel and/or all channels, hit map, mean amplitude, FWHM, 2D intensity maps, peak centroid, energy resolution measurements). Fig. 2 shows the coherent x-ray scatter detection system.

Fig. 2. Components of the coherent x-ray detection system.

III. CHARACTERISATION OF THE COHERENT X-RAY SCATTER DETECTION SYSTEM

Working in calibration mode, a low-noise precision pulser was used to give an absolute calibration of the multi-cell Si-pad array with a reasonable accuracy. Five calibration voltages, for better data averaging, corresponding to the energy range of interest were implemented with a threshold voltage of \( V_{th}=0.1 \text{mV} \). A calibration graph of the calibration voltages in mV versus the ADC centroid values was plotted and a linear regression was applied as shown in Fig. 3. It is clear that the front-end electronics chip provides good linearity to the detection system.
Once the detector was calibrated and the look-up tables were generated, the normal mode was switched on for the rest of the experiments. The next step was to assess and optimize the energy response of the Si-pad based low-angle scatter system within the energy range (12-45 keV) given in the design specifications and to determine its energy resolution by employing a variable energy x-ray source, Am-241, (358MBq) to produce the x-rays of specific energies. This source consists of a compact assembly containing a sealed ceramic primary Am-241 source. It excites characteristic x-rays from 6 different targets mounted on a rotary holder. Each target can be presented to the primary source in turn and the characteristic x-rays from the target are emitted through a 4 mm diameter aperture. To cover the energy rage of interest, we made use of the following targets: Mo (17.44 & 19.63keV), Ag (32.00 & 36.55keV), Ba (32.06 & 36.55keV) and Tb (44.26 & 50.65keV). The figures in parentheses correspond to K\textsubscript{α} and K\textsubscript{β} lines respectively. The energy response of the Si-pad array for all 126 channels and for different energies is shown in Fig. 4. The FWHM energy resolution measured for Mo and Tb is 3 keV for all channels and 1 keV for single channel. Apparently, the multi-element array can detect all energies between 17-45 keV and can resolve the K\textsubscript{α} and K\textsubscript{β} peaks of Tb, Ba, Ag and Mo.

Further, to determine the optimum working conditions with respect to the operating voltage, V\textsubscript{bias}, threshold voltage, V\textsubscript{th}, leakage current, I\textsubscript{L}, and temperature, T, as well as to assess the noise performance of the coherent scatter detection system as regards the operating conditions and the threshold set up for discrimination between scatter signal and noise, experiments were carried out to measure the number of noise events across the 126 channels of the multi-cell array without any signal from a pulser or a radiation source. Fig. 5 shows the noise behaviour of the coherent scatter detection system for different operating voltages, while Fig. 6 for different operating voltages and different threshold voltages.

Fig. 3. Calibration graph of the multi-element Si-pad array.

Fig. 4. Response of the multi-cell Si-pad array to different x-ray energies of interest.

Obviously the number of noise events measured is low for all the operating voltages given by the design specifications. It was decided to operate the Si-pad detector at V\textsubscript{bias}=150V which allows stable operation in full depletion and low-noise. By reducing the V\textsubscript{th} and/or increasing the V\textsubscript{bias}, the number of noise events is increased. However, for V\textsubscript{bias}=150V and in the V\textsubscript{th} range of interest (0.07-0.12mV) the number of noise events is extremely low.

Fig. 5. Noise performance of the coherent scatter detection system for different operating voltages as given by the design specifications.

Fig. 7 shows the noise behaviour of the coherent scatter detection system for different temperatures while Fig. 8 the distribution of noise events for different temperatures and leakage currents. Clearly, the number of noise events remains very low if the detection system operates at stable temperature, which is actually near the room temperature. For the range of temperatures of interest, i.e. at or near the room temperature, the leakage current of the Si-pad detector does not increase significantly and hence the number of noise events is very low.
Fig. 6. Noise performance of the coherent scatter detection system for different operating voltages and different threshold voltages.

Fig. 7. Noise performance of the coherent scatter detection system for different temperatures.

To quantitatively assess the low-angle x-ray scatter performance of the special-purpose designed multi-element S-pad arrays, the scattering profiles of water, some most commonly used standard materials (PMMA, nylon, polyethylene) and breast adipose tissue (from mastectomy) were measured. A high-resolution micro-focus Mo source operating at 30kVp was used. An absorption filter of Zr was placed in front of the x-ray tube to monochromate the x-rays from the continuum to an almost 17.44 keV peak (the energy of mammography). The measured scattering profiles in terms of linear scattering coefficient per unit solid angle, $\mu_s(\chi)$, for the above mentioned materials are shown in Fig. 9.

The scattering profiles measured show one predominant peak, where interference effects are most important and its position is characteristic of the material; then the intensity falls in an oscillatory way according to the free-gas model (IAM). These results are in excellent agreement with published data regarding the peak position and shape.

IV. SUMMARY

A coherent x-ray scatter detection system based on a high-resistivity multi-element 2D Si-pad array, a multi-channel low-noise pulse processing front-end electronics chip, the XA1.3, and a new DAQ system was designed and developed. It was shown that this novel detection system meets the design specifications combining good energy resolution with position information; very good spectral response to the x-ray energies of interest; excellent low-angle x-ray scatter performance; low-noise behaviour; and operates at near room temperature without the need of cryogenic cooling. The multi-element 2D Si array in combination with a suitable multi-angle collimator provides us with the capability of applying a mixture of angle and energy dispersion techniques and has the potential to collect multiple scatter signals simultaneously to maximize the content of diagnostic information at shorter measurement times. It is therefore demonstrated that this Si-pad based coherent scatter detection system lends itself well to the detection of diffraction signatures and its implementation to a dual-sensor x-ray breast imaging system that will combine transmission and coherent scattering procedures.

V. ACKNOWLEDGMENT

The authors would like to thank D. harmer and J. Hearne for their valuable contribution to the project.
Fig. 9. Measured scattering profiles of PMMA, breast adipose tissue, polyethylene, nylon and water using the Si-pad coherent scatter detection system.

VI. REFERENCES