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PH. D. DISSERTATION

Development of high-speed hybrid pixel detectors for experiments with synchrotron radiation

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ROZPRAWA DOKTORSKA

Budowa i rozwój szybkich detektorów hybrydowych dla potrzeb eksperymentów synchrotronowych

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Abstract

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Since the synchrotron radiation started to strongly influence research areas, many fields of science, such as physics, chemistry or biology, experienced rapid advancement of conducted experiments. The especially important progress occurred owing to the 3rd generation of synchrotrons offering about one billion times more intense beam than conventional X-ray sources. In modern facilities, also the storage ring filling pattern is settable. By generating short-duration pulses of highly intense synchrotron light, it is possible to study time-dependent properties of the materials. So-called time-resolved experiments allow analyzing dynamic changes at the material atomic level down to nanosecond resolution.

Despite an access to the high-quality beam, the experiments prepared at synchrotron beamline do not always run with the performance desired by the scientists. One of the causes are limited parameters of the devices detecting X-ray radiation. In practice, it is challenging to build a detector that satisfies all experiment requirements, therefore often the compromise between the detector features and scientists' desires is made. Over time, the development of better detectors has become an urgent need, which is intensely growing especially as synchrotron beam parameters are constantly improved.

The dissertation shows the Authors effort on the design of detectors systems dedicated to time-resolved experiments and their experimental verification. All three detectors are built based on the UFXC detector which is single-photon counting hybrid pixel array detector (HPAD) designed at AGH University of Science and Technology.

The first system designed and prepared by the Author is dedicated to Pump-Probe-Probe experiment and was designed as a response to request from CRISTAL beamline at Synchrotron SOLEIL, Saint-Aubin, France. The main features of the detector are its high frame rate, up to 21 000 fps, and very low 120 ns observation time. The detector allows isolating single packets of photons emitted in 150 ns intervals and consequently enables acquiring diffraction patterns taken at very short moments of time. Furthermore, it is the first HPAD-based detector that enables collecting not only the main one but also the reference image during Pump-Probe type of experiment.

The second system designed and prepared by the Author is dedicated for X-ray Photon Correlation Spectroscopy (XPCS) experiment performed at 8-ID-I beamline at Argonne Photon Source Synchrotron, Lemont, Il, US. The detector enables 1 200 000 fps frame rate in a burst mode, which is almost two decades higher rate than presented by any other HPAD-based detector. The hybrid mode

introduced by the Author allowed greatly increasing the time resolution for multi-speckle XPCS by using UFXC HPAD, reaching sampling times continuously spanning from 826 ns to 52.8 s, so nearly eight decades in delay time, what was never reached before.

The last system designed and built by the Author is a demo-version of a stand-alone low-cost embedded device utilizing a single software platform for all necessary targets including FPGA, Real-Time OS, and Windows OS. The system designed shows an excellent performance and allows the image transfer over standard TCP/IP interface as well as a robust and high-speed channel link interface with the speed exceeding 7 000 fps.

Abstrakt

Budowa i rozwój szybkich detektorów hybrydowych dla potrzeb eksperymentów synchrotronowych

Pojawienie się promieniowania synchrotronowego pozwoliło na przeprowadzania nowych badań w obrębie takich nauk jak fizyka, chemia czy biologia, przyczyniając się do ich gwałtownego rozwoju. Szczególnie istotny postęp miał miejsce po pojawieniu się trzeciej generacji synchrotronów, oferujących wiązkę o milion razy większej intensywności niż konwencjonalne źródła promieniowania rentgenowskiego. W nowoczesnych ośrodkach, możliwa jest ponadto modyfikacja samego wypełnienia cyklu synchrotronu. Dzięki generacji krótkich impulsów o dużej intensywności, możliwe jest badanie właściwości materiałów pozostających w zależności od czasu. Tak zwane eksperymenty time-resolved pozwalają na badanie dynamicznych właściwości materiałów na poziomie atomów oraz w rozdzielczości czasowej rzędu nanosekund.

Pomimo dostępu do wysokiej jakości wiązki, naukowcom pracującym w ośrodkach synchrotronowych nie zawsze udaje się uruchomić eksperyment z pożądaną jakością. Jedną z przyczyn są ograniczone parametry urządzeń przeprowadzających detekcję promieniowania. W praktyce, budowa detektora, który spełnia wszystkie stawiane mu wymogi jest trudna i niejednokrotnie wypracowywany jest kompromis pomiędzy oczekiwaniami naukowców, a rzeczywistymi możliwościami systemu detekcyjnego. Z biegiem czasu, problem budowy detektorów o lepszych parametrach staje się coraz bardziej naglący, tym bardziej biorąc pod uwagę fakt, że jakość samej wiązki nieprzerwanie ulega poprawie.

W niniejszej rozprawie Autorka przedstawia trzy autorskie systemy zbudowane dla potrzeb eksperymentów typu time-resolved wraz z wynikami pomiarowymi otrzymanymi z ich wykorzystaniem. Wszystkie trzy systemy zostały zbudowane przez Autorkę w oparciu o detektor UFXC, będący hybrydowym detektorem pikselowym (ang. HPAD) pozwalającym na pracę w trybie zliczania pojedynczych fotonów.

Pierwszy przedstawiony w rozprawie i zbudowany przez Autorkę system został zrealizowany na potrzeby eksperymentu Pump-Probe-Probe dla linii CRISTAL na synchrotronie SOLEIL, Saint-Aubin, Francja. Głównymi zaletami detektora jest wysoka liczba zliczeń obrazów na sekundę, rzędu 21 000 obr/sek, a także bardzo krótki, 120 nanosekundowy czas otwarcia przysłony. Detektor pozwala na wyizolowanie pojedynczego pakietu fotonów spośród pakietów emitowanych w 150 nanosekundowych odstępach czasowych, a tym samym umożliwia obserwację stanu struktury

atomowej kryształu w niezwykle krótkim przedziale czasowym. Ponadto, jest to pierwszy detektor typu HPAD pozwalający na zbieranie zarówno obrazu dyfrakcyjnego, jak i obrazu referencyjnego.

Drugi prezentowany system dedykowany jest pomiarom X-Ray Photon Correlation Spectroscopy (XPCS) przeprowadzanym na linii 8-ID-I na synchrotronie Argonne Photon Source w Lemont, Illinois, Stany Zjednoczone Ameryki Północnej. System umożliwia akwizycję obrazu z prędkością 1 200 000 obr/sek w trybie „burst", co jest wynikiem prawie dwie dekady większym niż prezentowane w innych istniejących detektorach typu HPAD. Dzięki dodatkowemu połączeniu dwóch trybów pracy w detektorze, możliwe stało się znaczne zwiększenie rozdzielczości czasowej w eksperymentach multi-speckle XPCS i rozciągnięcie osi czasu między 826 nanosekundami a 52.8 sekundy, czyli prawie osiem dekad, co do tej pory nie zostało nigdy zaprezentowane w tego typu eksperymencie.

Ostatnim omawianym detektorem jest projekt autonomicznego i niskobudżetowego urządzenia wykorzystującego graficzny język programowania dla wszystkich trzech warstw oprogramowania, włączając w to FPGA, system czasu rzeczywistego oraz system operacyjny Windows.

1. DISSERTATION THESES

Synchrotron radiation is unique as a large number of highly coherent photons is generated in very short and frequent bunches. Therefore, single photon counting hybrid pixel detectors are still considered to be too slow for high demanding time-resolved applications, requiring tens of thousands of frames per second and very short signal integration time together with dead-time of the front-end electronics in the range of 100 ns, or less. However, new designs of hybrid pixel detector readout integrated circuits enable operation with higher speeds and bring the possibility to use them in those high demanding time-resolved applications with synchrotron radiation. Therefore, the following theses are formed:

A. A single-photon counting hybrid pixel detectors are suitable for operation in a pump-probe-probe-kind experiment when a short integration time allowing single bunch separation together with high energy resolution, low spread of gain and DC offsets and sufficient noise performance are kept with synchrotron radiation.
B. A single-photon counting hybrid pixel detector with very high frame-rate and short dead-time of the front-end electronics allows greatly increasing time resolution and the measured contrast for multi-speckle X-ray photon correlation spectroscopy,
C. The use of universal, visual programming platform in the design of an embedded and a low-cost hybrid pixel detector readout system allows unifying design process, reducing the complexity of design and reducing the number of software tools.

2. ACHIEVEMENTS

Synchrotron applications require a lot of resources including the detailed knowledge of the operation of the synchrotron which varies between different establishments but also an experiment definition, synchronization methods, signaling, and high fidelity detector systems. All this requires the involvement of a specialized team of certain individuals in order to properly define and perform the new experiment. The Author was working as a member of different teams on providing new tools for very demanding experiments. Authors work inside those groups is summarized below:

I. Preparing the measuring modules
   1. The Author has designed modules utilizing UFXC32k IC - a single-chip hybrid pixel detector consisting of 32 768 measuring channels, and made a detailed characterization of the device including measurement of noise, gain, a dead-time of the front-end electronics and dispersion of the threshold level,
   2. The Author has proposed a new, fast iterative method of trimming of the threshold and gain dispersion suitable for low-memory embedded devices and has verified those methods as well as performed measurement of the final energy resolution of the detector,
   3. The Author has proved that the modules parameters measured in the laboratory are good enough for the detector to be used in the time-resolved experiments.

II. Pump-Probe-Probe experiment validation at Synchrotron SOLEIL, France
   1. The Author prepared the FPGA-based read-out system for the experiment including tests of a short-gate mode of operation, necessary triggering, and trigger delay to map a synchrotron current characteristic
   2. The Author has proved that the UFXC32k IC-based hybrid pixel detector can work with synchrotron radiation with a very short gate opening time and therefore it is suitable for a Pump-Probe-Probe experiment at Synchrotron SOLEIL. As a result of this work, a new project was agreed between AGH-UST and SOLEIL aiming a development of a large-area detector based on UFXC32k IC.

III. Improvement of an X-ray photon correlation spectroscopy experiments at Advanced Photon Source at Argonne National Laboratory, US
   1. The Author has prepared the FPGA-based system allowing operation in so-called burst mode with the speed of 1.2 Mfps and combined it with zero-dead time mode operating in 50 kfps resulting in a new hybrid mode of operation of the detector based on UFXC32k IC,
   2. The Author has proved it is possible to greatly increase the time resolution for multi-speckle XPCS by using UFXC hybrid pixel detector reaching sampling times

continuously spanning from 826 ns to 52.8 s, so nearly eight decades in delay time, what was never reached before.

Basing on this result the UFXC detector is a permanent system of the 8-ID-I beamline at APS available for researchers from around the world.

IV. Preparing a demo-version of a stand-alone embedded device,

1. The Author has verified a methodology of building a stand-alone embedded detector utilizing a single software platform for all necessary targets including FGPA, Real-Time OS, and Windows OS,
2. The Author has built an embedded low-cost detector capable of streaming data with the speed of 640 MB/s using Camera Link Full configuration and has made tests of this detector in Rigaku Corporation, Japan,
3. The Author has proved it is possible to define a design methodology which requires a minimum change to the design when the detector itself changes and requires the knowledge of a single software-platform to quickly finish the design;

Therefore, the Author of the dissertation has successfully provided useful tools for synchrotron experiments and so has proven theses of the dissertation. The ongoing work was presented by the Author during international conferences, namely IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS-MIC), International Workshop of Radiation Detectors (IWORID) and Mixed Design of Integrated Circuits and Systems (MIXDES) [1]. The results of the work were published in significant to the field journals having high impact factor, like Journal of Synchrotron Radiation [2], [3] and Journal of Instrumentation [4], [5]. Because of the positive involvement of the Author, the AGH-UST collaboration with SOLEIL Synchrotron and APS synchrotron is stronger and new projects are formed for the future.

3. MAIN ARTICLES

[1] **A. Kozioł** and P. Maj, 7.3kfps Readout Solution for 65k Pixel X-Ray Camera Working in Zero Dead-Time Mode, in *Mix. 2016, 23th Int. Cinference Mix. Des. Integr. Circuits Syst. B. Abstr.*, (Łódź, 2016).

[2] **A. Koziol**, M. Bordessoule, A. Ciavardini, A. Dawiec, P. Da Silva, K. Desjardins, P. Grybos, B. Kanoute, C. Laulhe, et al., Evaluation of the UFXC32k photon-counting detector for pump–probe experiments using synchrotron radiation, *J. Synchrotron Radiat.* **25** (2018) 413.

[3] Q. Zhang, E. M. Dufresne, S. Narayanan, P. Maj, **A. Koziol**, R. Szczygiel, P. Grybos, M. Sutton, and A. R. Sandy, Sub-microsecond-resolved multi-speckle X-ray photon correlation spectroscopy with a pixel array detector, *J. Synchrotron Radiat.* **25** (2018) 1408.

[4] **A. Koziol** and P. Maj, High speed systems for time-resolved experiments with synchrotron radiation, *J. Instrum.* **13** (2018) C02049.

[5] P. Maj, K. Kasiński, P. Gryboś, R. Szczygieł, and **A. Kozioł**, Single software platform used for high speed data transfer implementation in a 65k pixel camera working in single photon counting mode, *J. Instrum.* **10** (2015).