博士論文（要約）

STUDY ON NOVEL READOUT METHOD OF SUB-MM RESOLUTION GAMMA-RAY DETECTOR FOR PET/SPECT APPLICATION

(PET/SPECT 用サブミリ分解能ガンマ線検出器に関する研究)

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論 文 の 内 容 の 要 約

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Positron Emission Tomography (PET) is a non-invasive method for in-depth imaging of tissue function. As most other imaging techniques PET measures photons. The key difference is that these photons are emitted from positron and electron annihilation. The positron of the labeling isotope emitted in a б+-decay slows down in a tissue. After slowing down sufficiently it subsequently annihilates with a nearby electron producing two 511 keV gamma-rays. These gamma-rays are detected and initial labeling isotopeǿs position is determined. Different approaches to detect gamma-rays have been proposed. However, inorganic crystals with photon detectors are usually used. The increasing interest in PET systems creates the need for better performance of these devices.

Commercially available PET scanners are quite sufficient for the standard clinical applications. Clinical oncology, which tries to find and track tumors, consumes up to 90 % of PET usage. Another areas are more specific: for example, in neurology PET devices are used to measure brain activities and disease; in neuropsychology ï brain activity to psychological processes; in cardiology ï heart diseases and functions; in musculo-skeletal ï muscle behavior; in pharmacokinetics PET devices are used to study drug bio-distribution in the body; while in psychiatry PET devices are used to analyses the psychical conditions (schizophrenia, mood disorders). However, over the last decade the need for high resolution PET scanners have been increasing. For example, early diagnose of Alzheimerǿs disease or the tracking of the dynamics of a blood cells which could be performed using higher resolution PET imaging.

The key element of the PET system is the gamma-ray detector. Therefore, to develop a high resolution PET system a high resolution gamma-ray detectors are needed. The sub-mm resolution gamma-ray detectors would be ideal for the new high resolution PET systems.

Gamma-ray detectors are composed of various subsystems, which are synchronized for the best performance. Two main subsystems are distinguished: an optical circuit and an electrical circuit. The optical circuit is used to convert the energy of gamma-ray to low energy photons, while the electrical circuit is used to detect the low energy photons and to produce electrical signal. For the optical circuit scintillation crystals are the main choices, while various photo detectors (photomultiplier tubes, avalanche photodiodes, silicon photomultipliers etc.) can be used in the electrical circuit depending on the needs.

Cerium doped $Gd_3Al_2Ga_3O_{12}$ (Ce:GAGG) single-crystal scintillators were developed for high resolution detectors. These scintillators coupled with silicon photomultipliers will produce larger output signal compared with other commonly used scintillators due to generation of longer wavelength photons, which increases the energy resolution. In addition Ce:GAGG scintillators do not contain of naturally occurring radioisotope lutetium by that avoiding and reducing beta-gamma true coincidences in PET detectors.

A photo detector is often used in conjunction with scintillators to convert light, emitted by the scintillator upon interaction with radiation, to electrical signals. Silicon photomultipliers (SiPMs) are relatively new silicon based semiconductor photo detectors which are of great interest for high energy physics, astrophysics and medical applications because of their properties such as high gain, good quantum efficiency, fast response, compactness and insensitivity to magnetic fields.

Mm or sub-mm Ce:GAGG crystals coupled with mm or sub-mm SiPM are promising high resolution gamma-ray detectors for PET, Single-Photon Emission Computed Tomography (SPECT), block detectors and small animal PET systems. However, due to restrictions to photo detectors, the pixel size of the detector is currently much bigger than the scintillatorǿs. Therefore, light sharing method is usually used in order to achieve good resolution in such a system. Despite that, different limitations in light sharing systems degrade the signal. Best possible resolution could be achieved using one to one coupling between the scintillation crystal and the SiPM channel. On the other hand, individual readout in mm and sub-mm systems requires substantial amount of processing electronics where power consumption is high. Therefore, in such systems readout signal multiplexing is necessary to make such systems useful. It is clear that novel readout approaches are needed to achieve the sub-mm resolution PET systems.

The purpose of this work is to study the feasibility of small pixel, large format SiPM and dense scintillator crystal array for high resolution detectors.

Firstly, limitations of the conventional light sharing in charge division systems to achieve high resolution were studied. 48 by 48 array with 0.4 by 0.4 by 20 mm^3 Ce:GAGG scintillation crystals was connected using the light sharing using a glass to a 64-channel multi-pixel photon counter (MPPC) detector. The detector was readout using charge division circuit. Different glass thicknesses were tested to achieve the best possible resolution, while Geant4 simulations were used to analyses the results and limitations of the system.

Small pixel, large format PET system based on individual coupling between the SiPM and scintillation crystal was constructed. A 144-channel SiPM with 1.9 mm pitch with 1.6 by 1.6 by 15 mm^3 Ce:GAGG scintillation crystals was used for the new PET. Time-over-Threshold (TOT) ASIC based front-end electronics were used to readout the signals from the SiPM detector. The performance for the non-invasive measurement of radiotracer in blood of the new small PET system was analyzed. Such PET system should achieve sub-mm resolution, while being compact and lightweight.

Finally, a new architecture of the front detector module based on novel readout method is proposed. The new architecture is based on 0.5 mm pitch Ce:GAGG scintillation crystals individually coupled to the newly developed 0.5 mm pitch SiPM array with signal multiplexing using double side readout. In this study, the analysis of the new 16-channels 0.5 mm pitch SiPM device prototype and its compatibility with 0.4 by 0.4 by 20 mm^3 Ce:GAGG scintillator crystals as a gamma-ray detector are presented. Geant4 and 5Spice simulations were used to additionally characterize the new system. Signal multiplexing using double side readout setup is being considered, therefore, Geant4/5Spice simulations were used to analyze the feasibility for the multiple channel readout. In addition, the probable precision of the Depth of Interaction (DOI) measurements and the novel light guiding system were also analyzed using simulations.

Based on the results of this study, several important conclusions can be drawn:

- Geant4/5Spice simulations can be used to simulate and analyze gamma-ray detectors.

- Light sharing in charge division systems could achieve sub-mm resolution; however due to limitations are not suitable for large array detectors.

- 1.9 mm pitch individually coupled gamma-ray detectors readout using TOT-ACISs for PET system shows 0.86 mm spatial resolution at the center of FOV.

- This novel PET system shows promising results for the sub-mm imaging based on the good results of the coincidence, transmission and NEMA NU 4-2008 phantom imaging. However, blood vessel phantom imaging shows a need for further improvement of the detector for the blood dynamic measurement applications.

- The individual coupling of the 16 channels, 500 µm SiPM array and 0.4 x 0.4 x 20 mm^3 GAGG scintillator was confirmed to be sufficient to measure ^{137}Cs source.

- The Geant4/5Spice simulation approach indicates a good precision of the DOI measurements in the proposed novel double side readout system, while light guiding would improve energy resolution but would also decrease the timing resolution.