Modelling of monolithic scintillator crystal and silicon photomultiplier based PET detector modules

PhD thesis booklet

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2018.

Introduction

Positron emission tomography (PET) is a widely used 3D medical imaging technique both in conventional medical diagnosis and research. With this technique it is possible to map the distribution of the contrast agent injected to a living body. The contrast agent is prepared in a way that it takes part in biological processes, so from its distribution one can conclude on the states of the living body or individual organs.

The contrast agent is positron emitter. As an emitted positron recombines with one electron of the body, a pair of γ-photons is emitted. The role of the detector modules of the PET system is to absorb them and determine the time and position (point of interaction - POI) of absorption and the amount of energy transmitted to the detector. From this information the 3D distribution of the positron emitter can be reconstructed. The resolution of the 3D image largely depends on the resolution of the detector module's spatial temporal and energy resolution.

The γ-photon detection is based on scintillation crystals and photon counters. The scintillator crystal transforms the energy of the γ-photon to optical photons which is sensed by the photon counters. In order to improve the resolutions of PET detector modules their optical construction has to be optimized.

The conventional PET detectors are built from an array of closely packed needle-like scintillators with several square millimetres footprint and large area – several square centimetres – photomultiplier tubes. In these detectors the estimation of POI is achieved by the identification of the crystal needle in which the absorption happened. Thus the spatial resolution is limited by the footprint of the crystal and furthermore the position information along the longer side of the crystal is lost (so-called depth information).

Nowadays, the newly developed silicon photomultipliers are divided into pixels with a few square millimetre sizes or even below that. This new technology opens the way to the utilization of slab scintillators. This construction offers many advantages e.g.: cheaper scintillator crystal preparation, capability to retrieve depth information, etc. On the other hand it is more complex to create an optimized optical arrangement to such a setup. The resolution of each parameter of interest may vary with spatial position (all three coordinates). The goal of the optimization is to minimize this variation and in the meantime achieve the best possible resolutions.

Scope of the research

My work is related to the SPAnet project, where the goal is the development of a new, fully-digital silicon photon counter and a related slab scintillator-based, optimized PET detector arrangement. The goal of my work was to develop a simulation method that aids the mentioned optimization and design process. The work can be subdivided into three main fields: (1) the analysis of the optical properties of components and materials used in PET detector arrangements; (2) the creation of mathematical, simulation models of the same, and the development of a simulation tool that is able to model the novel PET detector constructions in detail. The final part (3) is the validation of the simulation tool and the applied models. I participated in the development of the photon counter as well, thus as a part of step (1) I analysed several possible photon counter geometries to identify optimal solutions for the novel PET detector arrangement.

Methods

As a basis of the optical simulation I used a commercial optical design tool, Zemax OpticStudio. I realized the optical model of the materials and the geometry of the sensor in this tool. MATLAB programming language was used to make all the additional modelling work which cannot be done directly in OpticStudio and to do the post processing of the acquired data.

To characterize the optical materials and components I used commercially available optical instruments, and where it was necessary I designed and built custom experiments and evaluation methods. Finally the validation of the simulation was done by using my custom built experimental setup that was constructed to cope with the special needs of this validation task.

New scientific results

1) *I worked out a method to determine axial dispersion of biaxial birefringent materials based on measurements made by spectroscopic ellipsometers; by using this method I found that LYSO:Ce scintillator material's Z index ellipsoid axis' direction changes 2.4^o monotonically from 400 nm to 700 nm.* [1]

2) *I determined the range of the single-photon avalanche diode (SPAD) array size of a pixel in the SPADnet-I sensor where both spatial and energy resolution of an arbitrary monolithic scintillator-based PET detector is maximized. According to my results one pixel has to have a SPAD array size between 32 × 32 and 64 × 64 [2,3,4]*

3) *I developed a novel measurement method to determine the photon detection probability's (PDP) and reflectance's dependence on polarization and wavelength up to 80^o angle of incidence of cover glass equipped, silicon photon counters; I applied this method to characterize SPADnet-I photon counter.* [5]

4) *I developed a simulation tool (SCOPE2) that is capable to precisely simulate the detector signal of SPADnet-type digital, silicon photon counter-based PET detector modules for point-like γ-photon excitation by utilizing detailed optical models of the applied components and materials; the simulation tool can be connected into one tool chain with GATE simulation environment.* [3,4,6,7,8]

5) *I developed a validation method and designed the related experimental setup for LYSO:Ce scintillator crystal-based PET detector module simulations performed in SCOPE2 (main finding 4); point-like excitation of experimental detector modules is achieved by using γ-photon equivalent UV excitation.* [3,4,9]

6) *By using my validation method (main finding 5) I showed that SCOPE2 simulation tool (main finding 4) and the optical component and material models used with it can simulate PET detector response with better than 13% average shape deviation, and the statistical distribution of the simulated quantities are identical to the measured distributions.* [7,8]

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