Investigation of Scintillation Light Multiplexing for PET Detectors Based on position sensitive avalanche photodiodes

Frezghi Habte, *Member, IEEE,* Peter D Olcott, *Member, IEEE,* Craig S Levin, *Member, IEEE,* Angela MK Foudray, *Student Member, IEEE*

***Abstract*— Dedicated high resolution compact PET systems are being developed for breast and small animal imaging that use lutetium oxyorthosilicate (LSO) crystals (1x1x3 mm^3) coupled to highly compact position sensitive avalanche photodiodes (PSAPDs) with 8x8 mm^2 active area and 200μm thickness. The full system will consist of thousands of PSAPDs. In this paper, we investigated methods to multiplex scintillation light from the LSO crystals in order to significantly reduce the number of PSAPDs required without compromising the system performance. Initial experiments were performed using dual layer slotted LSO crystals forming crystal pixels that are offset with respect to either layer by half crystal pixel width in either 1D or 2D configuration. For the 1D crystal configuration, the results show that all crystal pixels (1x1x3mm^3) except the edge crystal pixels can be resolved with an average of 3:1 peak to valley ratio when a specular reflector is used between the crystal slots. An average energy resolution of ($\sim$13%) is also obtained. Compared to the 1D offset crystal configuration, the 2D offset crystal configuration showed slightly better performance with an average energy resolution of ($\sim$12%) and peak to valley ratio of ($\sim$4.5:1). This result is comparable to the previous published data using discrete single layer crystal arrays. A relatively uniform photo peak energy distribution (standard deviation σ <0.3 volts) is also observed. The result showed that light multiplexing using dual layer LSO crystals with offset crystal slot configuration has great potential. In addition, the slot crystal offset mechanism will simplify the mechanical assembly of the crystals.**

***Index Terms*— Positron Emission Tomography, Lutetium Oxy orthosilicate, Position Sensitive Avalanche Photodiode**

I. INTRODUCTION

POSITRON Emission Tomography (PET) is becoming an increasingly popular tool for cancer detection and molecular imaging [1]–[3]. Hence, many research groups are involved in the development of high resolution and high sensitivity PET systems [4], [5]. Many of those new PET systems use arrays of small scintillation crystals such as lutetium oxyorthosilicate (LSO) [6] coupled to position sensitive photodetectors. Recently, silicon-based position sensitive avalanche photodiodes (PSAPDs) [7]–[9] are becoming popular for PET detectors due to their compact design, high optical quantum efficiency, wide spectral response, and are insensitive to magnetic fields.

We are developing dedicated compact PET systems for breast and small animal imaging that use closely packed LSO arrays coupled to highly compact PSAPD detectors in a novel detector configuration [10], [11]. Our goal is 1 mm^3 volumetric spatial resolution and >10% coincidence detection efficiency (system sensitivity) for a central point source. The major disadvantage of building a PET system using this detector configuration is that the system will require thousands of PSAPDs, a major cost of the system. The requirement to readout at least four channels from each PSAPD also significantly increases the cost of the readout electronics. PSAPDs have a great potential to be cost effective with volume production, but reducing the number of PSAPDs by at least a factor of two will significantly reduce the overall system cost.

In this paper, we investigated methods to multiplex scintillation light detection that allow two layers of LSO crystal to be read-out using only one PSAPD without compromising the system performance, while significantly reducing the number of PSAPDs.

II. PROPOSED SYSTEM DESIGN AND DETECTOR CONFIGURATION

The system design, without applying light multiplexing methods, consists of a highly compact PSAPD ($\sim$200μm thick chip mounted on a 50 micron thick flex cable and 8x8 mm^2 active area) coupled to a densely packed array of 1x1x3 mm^3 LSO crystals. The detector system is oriented in a novel configuration [12] that can directly measure the depth of photon interaction and promote >90% light collection efficiency. A rectangular system geometry is used for high sensitivity small animal PET system as shown in fig. 1b. Using a similar detector design, we are also developing a dual panel PET system dedicated for breast imaging. Each detector module consists of two PSAPD-LSO detectors (fig. 1a) oriented "edge-on" with respect to incoming 511 keV annihilation photons. When light multiplexing is applied, two layers of LSO crystals will be coupled to each PSAPD, reducing the number of PSAPDs in the system (see fig. 2).

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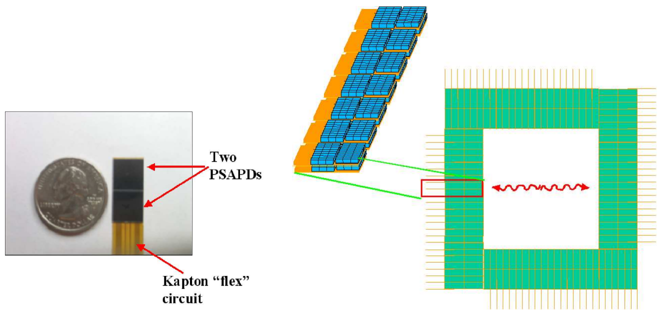
Frezghi Habte is with the Department of Radiology, the Molecular Imaging Program at Stanford University (fhabte@stanford.edu). Peter D. Olcott is with the Department of Radiology, the Molecular Imaging Program at Stanford University(pdo@stanford.edu). Craig S. Levin is with the Department of Radiology, the Molecular Imaging Program at Stanford University (cslevin@stanford.edu). Angela MK Foudray is with the Department of Radiology, the Molecular Imaging Program at Stanford University and Department of Physics at the University of California, San Diego (afoudray@stanford.edu).



(a) PSAPD detector (b) box geometry

Fig. 1. a) Highly compact dual-PSAPD detector mounted on flex circuit designed to hold two PSAPD chips. b) Proposed PET system geometry comprising many detectors oriented “edge-on” with respect to incoming 511 keV photons.

III. Material and Methods

We performed experiments to read two layers of LSO crystal arrays with only one PSAPD chip. Each dual-layer crystal consists of a slotted LSO crystal forming 1x1x3 mm^3 crystal pixels that are offset by half a crystal pixel width with respect to the other layer. We studied three different slotted crystal array configurations as shown in fig. 2.

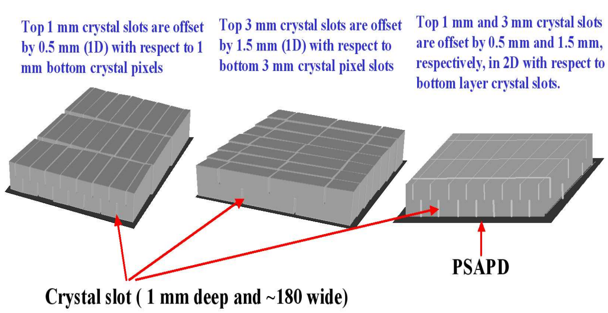


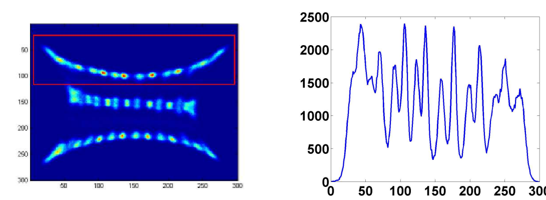
Fig. 2. (Left) Two-layer LSO crystal array consisting of three 8x2x3 mm^3 LSO crystals, each with seven cuts(slots) on the bottom and eight slots on the top. The offset in 1D is 0.5 mm along the 1mm crystal pixel width. (Middle) Two layer LSO crystal array consisting of eight 1x2x9 mm^3 LSO crystals with two slots on the bottom and three slots on top offset by 1.5 mm offset in 1D along the 3 mm crystal pixel direction. (Right) LSO crystal (8x2x9 mm^3) with slots offset in 2D with respect to bottom layer.

The bottom layer for all crystals are polished and optically coupled to the PSAPD 8x8 mm^2 active area. The slots and other sides of each crystal have ground surfaces. A 60 μm thick specular reflector was placed in the slots to reduce the light sharing between adjacent crystals and guide the light from the top layer uniformly to the bottom layer crystal elements. The array was covered with Teflon on the sides and with specular reflector on the top. A flood image was taken using a ^{22}Na (511 keV) source irradiating from the top. The energy resolution, crystal identification, and peak-to-valley ratio were evaluated for each crystal configuration.

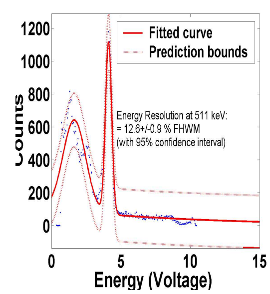
IV. Results

A. Flood image using 0.5 mm offset (1D) crystal configuration

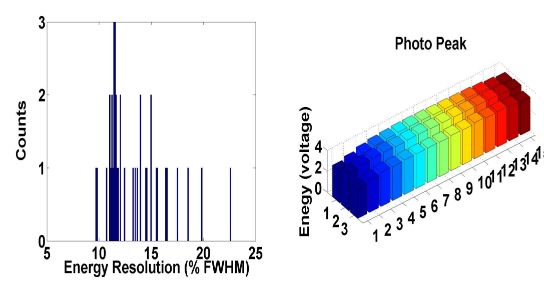
The 0.5 mm (1D) offset crystal configuration was flood irradiated normal to the face of the PSAPD using a ^{22}Na (511 keV) source. After energy gating, all 1x1x3 mm^3 crystal pixels except the edge crystal pixels are resolved with an average peak-to-valley ratio of 3:1 (fig.3 a and b). The 2D crystal flood images were segmented by drawing boundaries around the photo peak locations using a minimum distance to peak algorithm [13] to extract individual crystal energy spectra. An average energy resolution of 13% at 511 keV was obtained for this configuration with relatively narrow distribution of energy resolution values (fig. 3 c and d). A relatively uniform photo peak energy distribution ($\sigma = 0.289$ volts) was also observed (fig. 3 e).



(a) (b)



(c)

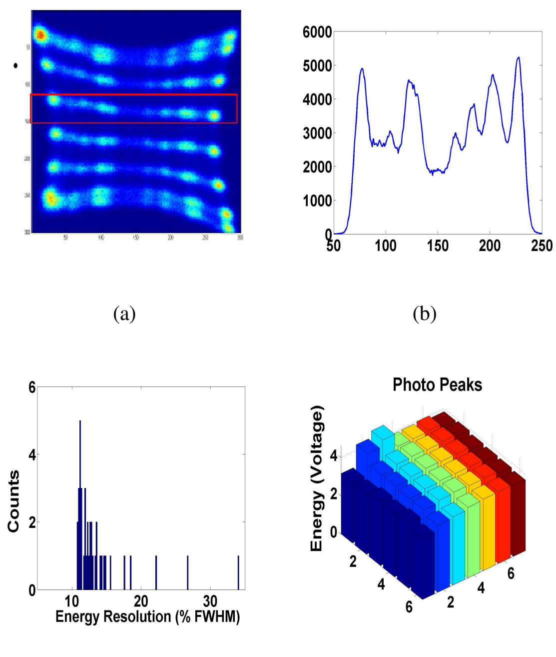


(d) (e)

Fig. 3. a) Flood image using 0.5 mm offset crystal configuration with respect to 1 mm crystal pixel width. b) Profile across the top row. c) Energy spectra of single crystal pixel obtained from segmentation of the 2D flood image. d) Energy resolution distribution of individual resolved crystal pixels. e) Photo peaks of each crystal pixel

B. Flood image using 1.5 mm offset (1D) crystal configuration

The flood image measurement using a 1.5 mm offset (1D) crystal configuration resolved the top crystal pixels with ~2.5:1 peak-to-valley ratio when energy gating was applied to individual crystal pixels. The photo peaks of the bottom crystals are stretched along the 3 mm direction, providing relatively poor peak-to-valley ratio (fig. 4 a and b). An asymmetric intensity profile across the 3 mm crystal length is also observed, possibly due to imperfect placement of reflectors between crystal pixels. An average energy resolution of 13% was obtained, which was calculated from the individual crystal energy spectra extracted from the segmented 2D flood image (fig. 4 c). Relatively uniform (σ =0.282 volts) photo peak energies were also observed (fig. 4 d).

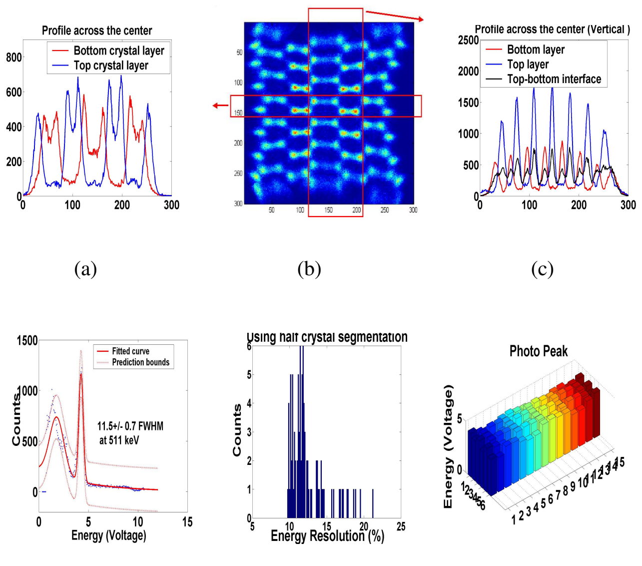


(a) (b) (c) (d)

Fig. 4. a) The flood image using 1.5 mm offset crystal (1D) configuration with respect to 3 mm crystal direction. b) Profile across the middle row. c) Energy resolution distribution of individual and d) Photo Peak energies of individual crystal pixel

C. Flood image using 2D offset crystal configuration

After energy gating and polynomial correction for linearity, the flood image measurement for 2D offset crystal configuration resolved all crystal pixels with an average peak-to-valley ratio of 4.5:1 (fig. 5 a,b and c). A relatively uniform match (in 2D) was observed between the top layer peak locations and the bottom layer valleys and vice versa. Due to strong optical coupling between the top and bottom layer, the peak locations of individual crystal pixel along the 3 mm length are stretched in the image and show two distinct peaks at the either end of each 3 mm crystal. This allows sub-crystal segmentation to break the image into half crystal pixels (1x1x1.5 mm^3). The half-crystal pixel segmentation provided equivalent energy resolution results to full crystal pixel segmentation. An average energy resolution of 12% FWHM at 511 keV was obtained, which is systematically better than the 1D offset crystal configurations (fig. 5 d and e). A relatively uniform ($\sigma = 0.32$ volts) photo peak energies is also observed for this configuration (fig. 5 f).



(a) (b) (c) (d) (e) (f)

Fig. 5. a) Flood image using 0.5 mm offset crystal configuration with respect to 1mm crystal direction. b) Profile across the top row

V. Conclusion

Results from a flood measurements of the dual layer crystal configurations show that the 2D offset slotted crystal arrays coupled to a single PSAPD detector resolved all 1x1x3mm^3 crystal pixels with relatively good peak-to-value ratio (>4.5:1). A comparable energy resolution (~12%) performance is obtained compared to a previous published results using a single layer discrete LSO crystal array coupled to PSAPDs [12]. Due to strong optical coupling between the top and bottom layers, the peak locations of individual crystal pixels for 2D crystal configuration are stretched forming mini twin peaks for each crystal pixel. This allowed us to perform image segmentation further to half-crystal pixels without degrading the energy resolution performance. The immediate advantage of half-crystal segmentation is that it provides selectable depth of interaction resolution (between 1.5 and 3 mm). The 2D offset crystal configuration provided slightly better peak-to-valley ratio and energy resolution, compared to the 1D offset crystal configuration. This may be due to superior optical coupling between top and bottom layers in 2D offset crystal configuration, which provides relatively uniform light spread within the crystal array. Timing and spatial resolution performance is being characterized to fully evaluate the proposed light multiplexed detectors. In addition to light multiplexing, using slotted sheet crystal will significantly simply the assembly of crystals in building the fully system.

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