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Publication Date

2000-10-30

Peer reviewed

A LSO Scintillator Array for a PET Detector Module with Depth of Interaction Measurement*

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***Abstract*--We present construction methods and performance results for a production scintillator array of 64 optically isolated, 3 mm x 3 mm x 30 mm sized LSO crystals. This scintillator array has been developed for a PET detector module consisting of the 8x8 LSO array coupled on one end to a single photomultiplier tube (PMT) and on the opposite end to a 64 pixel array of silicon photodiodes (PD). The PMT provides an accurate timing pulse and initial energy discrimination, the PD identifies the crystal of interaction, the sum provides a total energy signal, and the PD/(PD+PMT) ratio determines the depth of interaction (DOI). Unlike the previous LSO array prototypes, we now glue Lumirror reflector material directly onto 4 sides of each crystal to obtain an easily manufactured, mechanically rugged array with our desired depth dependence. With 511 keV excitation, we obtain a total energy signal of 3600 electrons, pulse-height resolution of 25% fwhm, and 6–15 mm fwhm DOI resolution.**

I. INTRODUCTION

When constructing scintillator arrays, "plumbers" Teflon tape hand wrapped around individual detectors is a standard reflector choice for research PET cameras [1]; it is not a realistic choice for large cameras and/or cameras that use very small crystals. Research groups also use reflector molds made of a white compound [2]-[5], but this does not produce light output with our desired depth dependence. Some commercial cameras use block scintillator arrays with sawcut grooves packed with reflector powder [6], which is basically unsuitable for arrays of individual crystals. Hence, we developed an alternative scintillator array assembly procedure that uses a new reflector material.

Our production lutetium oxyorthosilicate (LSO) scintillator [7] arrays have been developed for a PET detector module capable of measuring depth of interaction on an event by event basis [8]. With this design, a single photomultiplier tube provides an accurate timing pulse and initial energy discrimination for an 8x8 array of 3 mm square LSO scintillator crystals, an 8x8 silicon photodiode array identifies the crystal of interaction, the ratio of the photomultiplier tube (PMT) and photodiode signal (PD) measures interaction depth, and the sum (PD+PMT) provides a total energy signal. Fig. 1 shows a photograph of the detector module. We are planning to use this PET detector module in several tomograph designs [9]-[11]; thus we have transformed the prototype detector into one that can be produced in quantity.

II. LSO ARRAY PRODUCTION

A. Surface Finish

The Positron Emission Mammography camera [10], the smallest of our camera designs, uses 2688 crystals. As a result, we prefer a chemically etched surface finish to a mechanical polish in order to reduce processing and handling costs. Chemical etches have been similarly developed for BGO [12] and GSO [13] scintillators. We etch the LSO crystals in a 200°C pyrophosphoric acid bath, followed by a cleaning process consisting of a 5 minute bath in boiling water, a 5 minute bath in concentrated HCl, a water rinse, and an ethanol cleaning [14, 15]. The pyrophosphoric acid is prepared by heating concentrated phosphoric acid (85% in water) in an uncovered vessel until the water is driven off and its volume is reduced by at least 15%. We etch the LSO

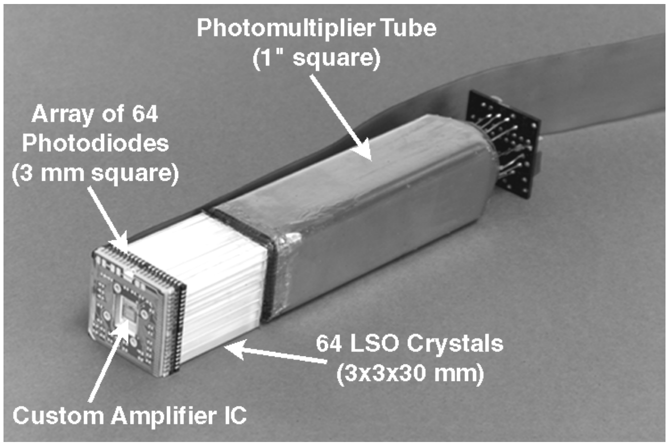

Fig. 1. Photograph of the PET detector. Each crystal is attached to a photomultiplier tube which provides timing and initial energy information, and to a photodiode which identifies the crystal of interaction. The PMT and PD signals are combined to measure the depth of interaction and total energy. The custom integrated circuit is mounted on a 1" square circuit board with a 0.008" Kapton tail, which goes between adjacent detector modules and acts as a cable connecting the IC to the remainder of the readout electronics.

Manuscript received October 25, 2000. This work was supported in part by the U.S. Department of Energy under contract No. DE-AC03-76SF00098, in part by Public Health Service Grant Nos. P01-HL25840, RO1-CA67911, and RO1-NS29655, and in part by Breast Cancer Research Program of the University of California Grant no 1RB-0068.

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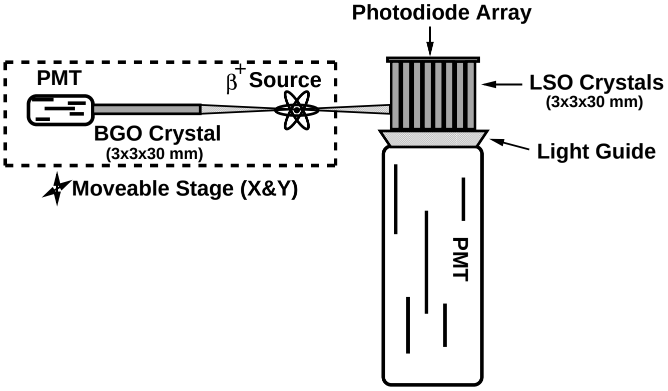

Fig. 2. Experimental set-up. The β^+ source, 3 mm x 3 mm x 30 mm BGO crystal, and PMT provide an electronically collimated beam whose position is adjusted by moving the stage. This allows a 5 mm fwhm portion of the detector module to be excited at an arbitrary depth of interaction.

crystals in batches of 64 for 5 minutes, which gives light collection properties similar to that of a mechanical polish. We find that further etching reduces the crystal size without significantly affecting the surface finish.

B. Light Collection Characterization

We test the light collection of single LSO crystals using the experimental method previously described for studying light collection efficiency and pulse-height resolution (*i.e.,* a mechanically collimated beam of 511 keV photons exciting a specific depth) [14]. Single crystals and multiple-crystal arrays are also tested using the experimental set-up shown in Fig. 2, with a PD array attached and/or with black tape used as a “mock” PD to imitate the optical properties of the PD array. The detector module is excited with a beam of 511 keV photons that is electronically collimated using a single 3 mm x 3 mm x 30 mm BGO crystal coupled to a photomultiplier tube, allowing a 5 mm fwhm portion of the detector module to be excited at an arbitrary depth of interaction [8]. The PMT signal is read out whenever the photomultiplier tube detects an energy deposit greater than 150 keV in time coincidence with the collimating photomultiplier tube.

The light collection is studied as a function of excitation depth. The LSO crystal(s) are excited at 5 mm incremental depths, and the photopeak position (*i.e.,* the center ADC bin of the photopeak) and pulse-height resolution are measured at each depth. The photopeak position varies as a function of excitation depth, as illustrated in Fig. 3(a) for a typical single LSO crystal. The photopeak position dependence on excitation depth is plotted in Fig. 3(b). The maximum light output is defined as the photopeak position when excited at the PMT end. The ratio of the photopeak position when excited at the PD end relative to the PMT end is defined as the DOI ratio.

C. Reflector

During our LSO array prototype development, we investigated the use of many different reflector materials. Our gold standard is several layers of “plumbers” Teflon tape hand wrapped by an expert around an individual crystal. This produces the highest maximum light output for our narrow (3 mm x 3 mm x 30 mm) LSO crystals, as well as our desired depth dependence. However, hand wrapping individual crystals is both time consuming and difficult to do consistently. Hand wrapping with reflector also limits the reduction of crystal size for future cameras. In addition, the mechanical properties of plumbers Teflon tape are not ideal. It stretches and creeps, so it can be difficult to accurately cover only 4 sides of each crystal (since we want the PD and PMT ends exposed). The Teflon also becomes transparent when glue wicks through it and when squeezed, which occurs when making a compact 64 crystal module. Fig. 4 demonstrates some of these potential problems with plumbers Teflon tape.

Therefore, we originally planned to use 8 mil (i.e., 0.008 inches) thick Teflon tape custom made in 30 mm wide rolls. We hand wrapped several single crystals with this 8 mil Teflon and tested their light output as a function of depth, but measured inconsistent results. The maximum light output and DOI ratio were only ~25% lower (than if wrapped with plumbers Teflon tape) as long as the 8 mil Teflon was wrapped tightly with no large gaps between the reflector and crystal. However, it was difficult to tightly wrap using the stiff 8 mil Teflon so we attributed the occasional lower depth dependence measurement on poor wrapping, and expected the light output performance to roughly match that of our gold standard (~4 layers of 0.001 inches thick plumbers Teflon wrap) when using 8 mil Teflon between crystals.

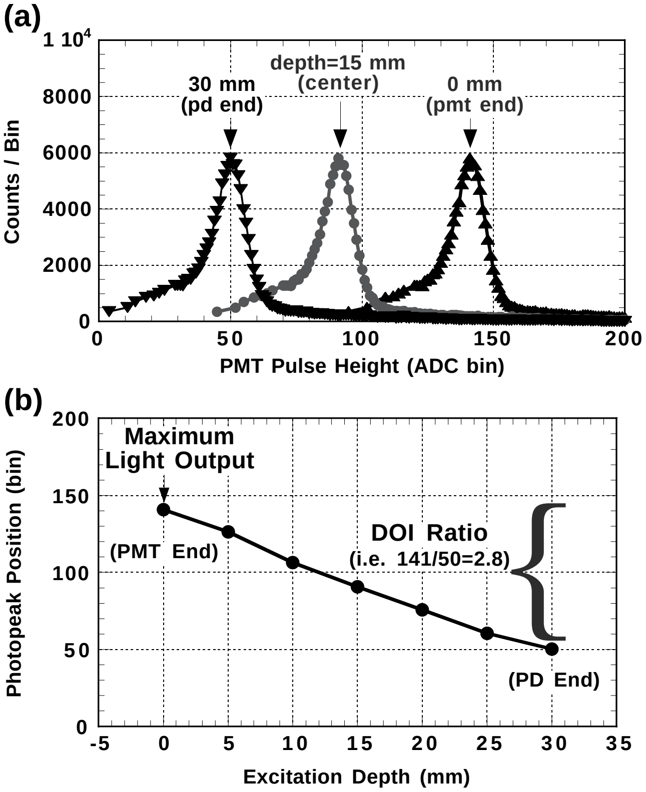

Fig. 3. (a) A 511 keV pulse-height spectrum for a typical LSO crystal as observed by a photomultiplier tube at 3 excitation depths. (b) The photopeak position as a function of excitation depth for a typical LSO crystal. The ratio of the photopeak position when excited at the PD end relative to the PMT end (*i.e.,* DOI Ratio) is indicated.

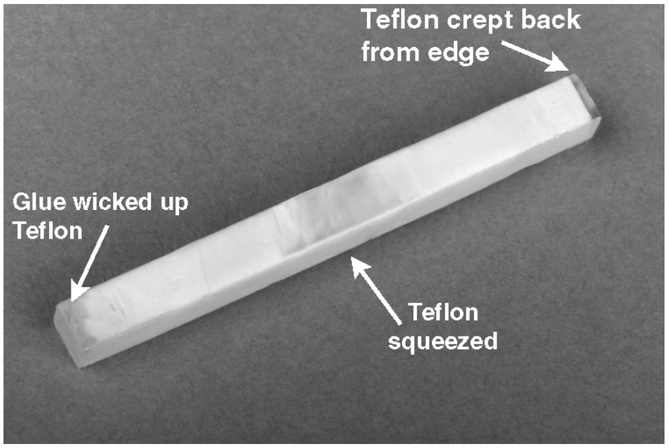

Fig. 4. A 3 mm x 3 mm x 30 mm LSO crystal hand wrapped with "plumbers" Teflon tape. On the far end, the Teflon tape has crept back from the edge. On the opposite end, glue wicked through the Teflon making it transparent. In the middle, the Teflon is transparent from being squeezed.

The 64 element LSO arrays were built with 8 mil thick Teflon cut into 3 mm x 30 mm and 24 mm x 30 mm sized pieces using an aluminum cutting jig and a razor blade. The width of the custom-made Teflon rolls is not consistently close enough to 30.0 mm so it is hand trimmed in this dimension as well; the plasticity of Teflon makes it difficult to cut to size accurately. We used additional jigging and tweezers to assemble an 8x8 LSO array, with 3 mm x 30 mm Teflon pieces placed between LSO crystals within a row and 24 mm x 30 mm Teflon pieces placed between rows.

LSO arrays assembled with 8 mil thick Teflon pieces consistently produce a lower maximum light output as well as less depth dependence compared with a crystal hand wrapped with plumbers Teflon. Fig. 5 shows that the maximum light output drops 37% and the DOI ratio drops from 2.8 to 1.7 when plumbers Teflon wrap (squares) is replaced by 8 mil thick Teflon pieces (circles). After extensive testing, we determined that the 8 mil thick Teflon does not have the same reflection properties as the plumbers Teflon wrap. This testing, in which we also evaluated the affect of many detector components on the light output, is described in Section II.D.

We therefore switched to a 180 μm polyester film called Lumirror [16]. Lumirror maintains its reflection properties even when exposed to many solvents, glues and greases. In our geometry, the reflection efficiency of Lumirror is similar to that of Teflon. In addition, Lumirror holds dimensions well, so it is easy to handle and laser cut to size. This allows us to use the jigging and assembly process previously planned for the 8 mil Teflon without many of the described problems; thus we don't have to hand wrap crystals with reflector. When LSO arrays are assembled with Lumirror pieces with an air gap, the DOI ratio is still low (*i.e.,* 1.8) compared with a crystal hand wrapped with plumbers Teflon tape. Fig. 5 (triangles) demonstrates this for a single crystal. However, we achieve our desired depth dependence when constructing the LSO array with Lumirror pieces glued directly onto all 4 sides of each crystal. Fig. 5 demonstrates that a single crystal with Lumirror pieces glued on 4 sides using Epotek 301-2 epoxy (diamonds) gives the same DOI ratio (*i.e.*, 2.8) as the crystal with plumbers Teflon wrap (squares), with an acceptable 20% decrease in maximum light output. In addition, an LSO array assembled with Epotek 301-2 and Lumirror pieces is mechanically rugged; thus allowing us to mechanically polish both ends of the array to ensure good coupling with the PMT and PD array. A photograph of a production LSO array is shown in Fig. 6.

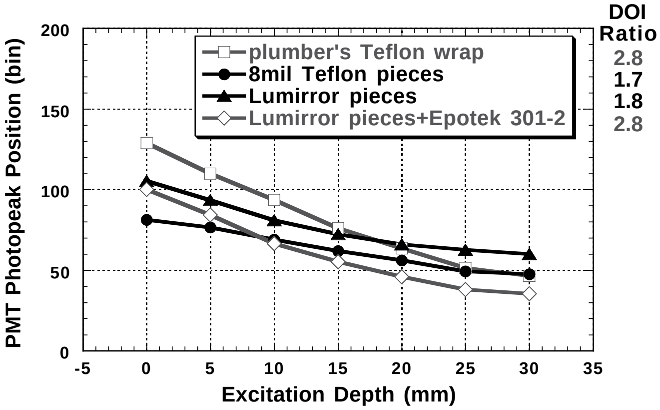

Fig. 5. Photopeak position of a single crystal as a function of excitation depth, as measured by the PMT with black tape on the opposite end. The different lines represent different reflector conditions: plumbers Teflon wrap (squares), 8 mil Teflon pieces with air gap (circles), Lumirror pieces with air gap (triangles), or Lumirror pieces glued on four sides with Epotek 301-2 (diamonds).

D. Light Collection Evaluation

Using the experimental set-up shown in Fig. 2 (with and without a real PD array), we have investigated how many factors affect the light output of LSO single crystals, 3x3 and 8x8 arrays. We have tested several alternatives for many of our detector components but we will not list the litany of them here. We only list a brief summary of our results to provide an overview of the "extensive testing" mentioned in the previous section.

Concerning the crystal PD and PMT ends, we find that good coupling to the photodetectors is essential to attain a high maximum light output. In contrast, the light collection is not significantly influenced by: (a) the existence of a quartz

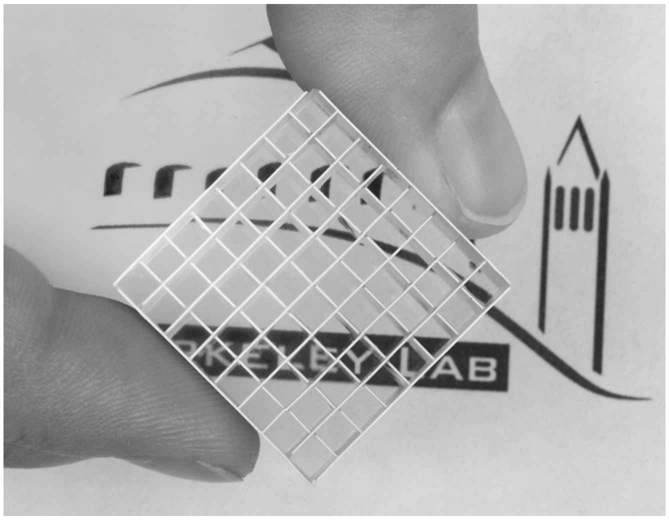

Fig. 6. A photograph of a production LSO scintillator array built using Lumirror pieces glued directly onto all four sides of each crystal. The Berkeley Lab logo is clearly visible through the array.

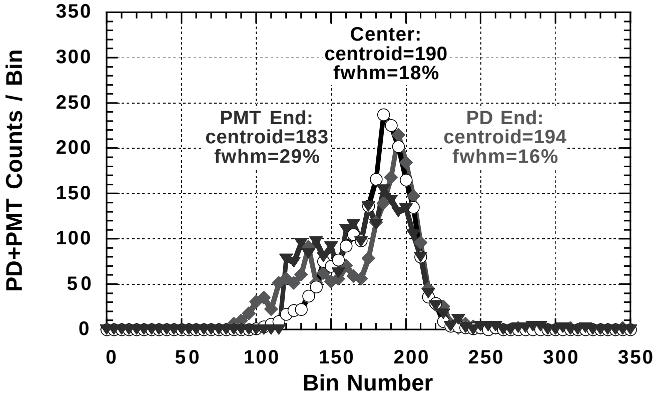

Fig. 7. Pulse-height spectrum of the summed signal PD+PMT from a typical single crystal when the detector module is illuminated by 511 keV photons at a fixed depth. The three depths correspond to the PMT end (triangles), center (circles) and PD end (diamonds). A clear photopeak with ~21% fwhm energy resolution is observed at all three depths, and the position of the photopeak centroid is approximately independent of the excitation depth. The energy resolution is 25% fwhm when averaging over six crystals at three depths.

light guide between the PMT and LSO array, (b) the thickness of glue used between the PMT and LSO array, and (c) the material used to couple the LSO array to either the PD or PMT. We also measure similar light output curves when using a silicon "mock" PD, black tape, and a real PD on the end opposite to the PMT.

Concerning the crystal sides, the type of reflector and reflector coupling method influence the light collection as discussed previously. If Teflon tape with an air gap is used, wicking of the PD/PMT coupling glue can significantly alter the depth dependence. We have also used several glues to apply 8 mil Teflon or Lumirror pieces to all sides of a LSO crystal. Sylgard 186 with Lumirror pieces is found to have a similar affect on the light output as Epotek 301-2 with Lumirror pieces; Epotek 301-2 was largely chosen to create a mechanically rugged assembly for the LSO array. The light collection is not significantly affected by light from adjacent crystals leaking in through the reflector "cracks" on the crystal edges or through transparent spots in the reflector caused by squeezing.

Finally, the "environment" does not play a significant role on the light collection. Neither self-radiation from ^{176}Lu nor Compton scatter from other LSO crystals in the module affects the depth dependence. The 511 keV source distance doesn't influence the depth dependence either, even though it does affect the spot size of the detector module that is excited (Fig. 2).

III. Detector Performance

The performance of a production LSO array was evaluated in a full detector module (Fig. 1). A prototype PD readout IC was used; this prototype has high electronic noise and is only capable of selecting one channel at a time. We expect better detector module performance with the new PETRIC IC, which is now complete [17].

The experimental set-up used to test the detector module is shown in Fig. 2. We measure the PD, PMT, total energy (*i.e.*, PD+PMT) and position estimator (*i.e.*, PD/(PD+PMT)) at 5 mm incremental depths for 6 crystals positioned through out the array, then average over the 6 crystals. Discernable (37% fwhm) photopeaks centered at 2400 e$^-$ and 1157 e$^-$ are observed by the PD when the module is excited at the PD and PMT ends respectively. The PMT signal is multiplied by a constant factor to make the PMT amplifier gain agree with the PD amplifier gain. Easily discernable (19% fwhm) photopeaks centered at 1227 e$^-$ and 2467 e$^-$ (after scaling) are then observed by the PMT when the module is excited at the PD and PMT ends respectively. The scaled PMT signal is added to the PD signal on an event by event basis. Fig. 7 shows the pulse-height spectrum of the summed signal (PD+PMT) from a typical single crystal when the detector module is illuminated by 511 keV photons at a fixed depth. The three excitation depths shown correspond to the positions 0, 15, and 30 mm, representing the PMT end, center and PD end respectively. A clear photopeak with 16 to 29% fwhm energy resolution is observed at the 3 depths, and the position of the photopeak centroid is approximately independent of the excitation depth. The energy resolution is 25% fwhm when averaging over 6 crystals at 3 depths.

The interaction position is measured on an event by event basis by computing a depth estimator, PD/(PD+PMT). Fig. 8(a) shows the distribution of the depth estimator for a typical single crystal with the module excited at the PMT end, center and PD end. The centroid (fwhm) is 0.32 (0.12), 0.50 (0.10), and 0.69 (0.08) for the PMT end, center, and PD

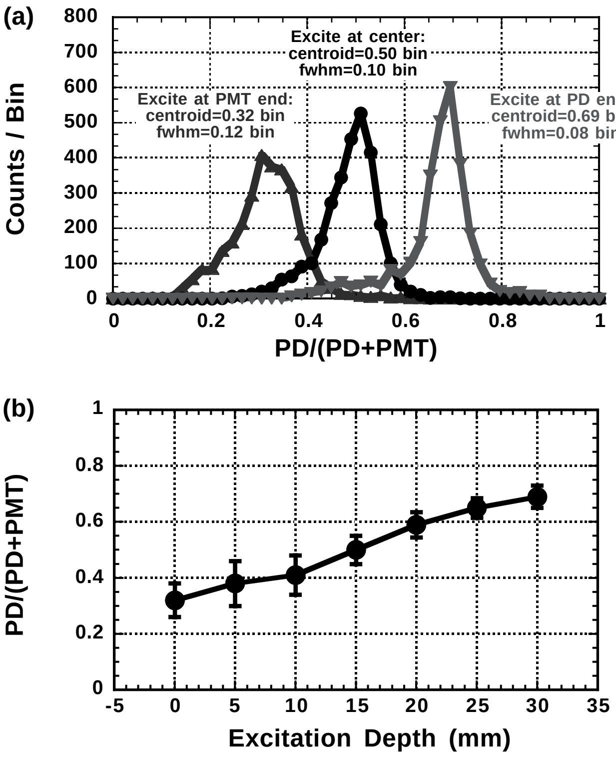

Fig. 8 (a) Distribution of the depth estimator PD/(PD+PMT) for a single crystal at three different excitation depths. The movement of the centroid indicates that the estimator is depth dependent, while the width of the distribution influences the accuracy. (b) Position estimator of the same single crystal shown for seven excitation depths. The error bars denote the fwhm. The DOI resolution is 6 to 10 mm fwhm for this single crystal, and 6 to 15 mm fwhm when averaging over six crystals.

end respectively. We see that the ratio depends on excitation depth as expected. Fig. 8(b) shows the value of the position estimator versus excitation depth for the same crystal, with error bars denoting the fwhm. Dividing the fwhm of the depth estimator by the slope yields the DOI resolution of 6 to 10 mm fwhm. When averaging over 6 crystals, the DOI resolution is 6 to 15 mm fwhm. The majority of the events occur at the end with the best resolution.

IV. FUTURE WORK

We have glued Lumirror reflector pieces onto 4 sides of individual 3 mm x 3 mm x 30 mm LSO crystals using Epotek 301-2 epoxy to construct 8x8 production LSO arrays. We did this because the individual LSO crystals had already been cut and etched in order to build our Positron Emission Mammography camera [10]. For future cameras, we can simplify fabrication by handling LSO disks rather than single crystals when gluing on the Lumirror as well as etching the LSO. Namely, we can cut a LSO boule into 3 mm thick disks, cut each disk into 30 mm wide bars, and acid etch each bar. Eight of these LSO bars are then glued together with Lumirror sheets between each bar (coating the LSO bars and Lumirror sheets with Epotek 301-2). The glued bar block is then cut into bars in the perpendicular direction, and these new LSO-Lumirror bars are etched. Finally, eight LSO-Lumirror bars are glued together with Lumirror sheets between each bar; thus creating an etched 8x8 LSO-Lumirror array without having to handle individual LSO crystals or small Lumirror pieces. This process should be possible since Epotek 301-2 and Lumirror can withstand the etching process, provided a reduced acid etch temperature is used with a correspondingly longer etch time. A mechanical polish could also be used on the LSO bar surfaces.

V. CONCLUSION

We have developed production techniques for a LSO scintillator array assembly using Lumirror reflector pieces glued onto all 4 sides of each LSO crystal with Epotek 301-2. Lumirror has reflection efficiency similar to Teflon, and maintains reflection properties if exposed to many solvents, glues and/or greases. We have demonstrated good detector module performance using a production LSO array. With 511 keV excitation, we obtain a total energy signal of 3600 electrons, pulse-height resolution of 25% fwhm, and 6 to 15 mm fwhm DOI resolution. This performance may improve with the new custom integrated circuit. There is a patent pending for the use of Lumirror polyester film as a reflector material for scintillator arrays, as described in this paper.

VI. ACKNOWLEDGMENT

This work was supported in part by the Director, Office of Science, Office of Biological and Environmental Research, Medical Science Division of the U.S. Department of Energy under contract No. DE-AC03-76SF00098, in part by the National Institutes of Health, National Cancer Institute under grant No. R01-CA67911, and National Institutes of Health, National Heart, Lung, and Blood Institute under grant No. P01-HL25840. Reference to a company or product name does not imply approval or recommendation by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

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