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Light-Sharing Interface for dMiCE Detectors using Sub-Surface Laser Engraving

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Abstract

We have previously reported on dMiCE, a method of resolving depth or interaction (DOI) in a pair of discrete crystals by encoding light sharing properties as a function of depth in the interface of this crystal-element pair. A challenge for this method is the cost and repeatability of interface treatment for a crystal pair. In this work, we report our preliminary results on using sub-surface laser engraving (SSLE) as a means of forming this depth-dependent interface in a dMiCE detector. A surplus first-generation SSLE system was used to create a partially reflective layer 100-microns thick at the boundary between two halves of a 1.4-by-2.9-by-20 mm³ LYSO crystal. The boundary of these paired crystal elements was positioned between two 3-mm wide Geiger-Müller avalanche photodiodes from Hamamatsu. The responses of these two photodetectors were acquired for an ensemble of 511-keV photons collimated to interact at a fixed depth in just one crystal element. Interaction position was then varied to measure detector response as a function of depth, which was then used to maximum-likelihood positions events. Despite use of sub-optimal SSLE processing we found an average DOI resolution of 3.4 mm for front-sided readout and 3.9 mm for back-sided readout. We expect DOI resolution can be improved significantly by optimizing the SSLE process and pattern.

I. Introduction

dMiCE is a discrete scintillation detector design that uses depth-dependent light sharing between a pair of crystals to encode depth-of-interaction (DOI) information in the light readout from one end of this crystal pair. Previous work [1] to select a conventional surface treatment that would optimize depth resolution for a pair of 2-by-2-by-20 mm³ crystals resulted in the use of multiple layers of shaped mirror film reflectors (VM2000 by 3M) and

a coating of high-index optical adhesive (Meltmount-1.705 by Cargille Labs) sandwiched between a pair of partially roughened crystals (Figure 1). The measured detector response as a function of interaction depth shows excellent depth sensitivity. However, fabrication of this crystal pair was laborious and difficult to repeat without a refined fabrication process. Furthermore, the non-scintillating interface material reduced overall photodetection efficiency.

In this work, we examine the use of sub-surface laser engraving (SSLE) to control light distribution without having to cut and manually form an interface. SSLE is a fast and relatively inexpensive process that has been used to produce 3D art in crystal blocks and recently has been used to discretize scintillation crystals [2,3]. A pulsed focused laser is used to create a pattern of microscopic optical defects that can reflect and scatter light. We have proposed to use SSLE as a means of shaping the light response function in scintillation detectors. Specifically, in this work, we report use of SSLE to control light sharing in dMiCE detectors.

II. Materials and methods

We fabricated several dMiCE crystals using sub-surface laser engraving. Before and after engraving, we measure photopeak detector response statistics of these samples to 511-keV gamma rays as a function of depth. An independent set of photopeak events at each depth were then positioned by maximum-likelihood estimation. Depth resolutions of these detector samples are reported as a function of depth.

A. Engraving

We have made use of a surplus first-generation SSLE system by Crystalix Evolution GmbH (Figure 2) to form one or two layers of ~100-micron-sized optical defects on a grid down the middle of a 1.4-by-2.9-by20 mm³ LYSO crystal (Figure 3). Optical aberrations in the flat-field lens and an unstable Q-switch of this 13-year system caused the engraved interface to be non-uniform. We are currently working with Crystalix Evolution GmbH to manufacture a SSLE system (Figure 4) with optimized optics and laser pulse characteristics to minimize collateral damage in the crystal in order to decrease point spacing and increase optical density in our future SSLE work.

B. Detectors

We calibrated and evaluated seven 20-mm-tall dMiCE crystals (Table 1). We also examined the responses of crystals 1a, 1b, and 1c before SSLE. Due to crystal availability, sizes of the two mechanically coupled crystal pairs (MFa and MFb) are different from the SSLE crystal pairs.

Two photodetectors (*PD1* and *PD2*) are used to read out the partitioned end of a dMiCE crystal. Our final detector configuration will consist of a 1-to-1 coupling of crystal halves (1.4×1.45 mm² area) to a photodetector array (Figure 5a). Other than sample MFb, for the testing done in this work, we used two pixels of a 16-channel Hamamatsu C11206-0404FB MPPC photodetector array (Figure 5b). All other faces of the crystals were covered in 4

layers of Teflon tape. For sample MFb, a 2-pixel MAPD-N device from Zecotek Photonics Inc. was used.

The inactive gap between photodetectors is aligned with the interface such that scintillation light must either penetrate the interface or go all the way around the top of the interface (opposite the photodetectors) to reach the abutted photodetector. For clarity, we term the crystal over PD1 as the *Left* crystal, and the crystal over PD2 as the *Right* crystal.

C. Calibration

For all except sample MFb, a double-ended 0.5-mm-borehole Tungsten collimator was used to collimate a Na-22 point source to produce a collimated 511-keV gamma-ray beam (Figure 6). A 4-by-4-by-20 mm³ LYSO coincidence detector read out by a Hamamatsu R9880U-110 photomultiplier tube was placed at the exit of the backend borehole in order to reduce the photon flux triggering the acquisition electronics. Moving this coincidence detector further back does not significantly improve beam size, which is primarily due to the geometry of this double-ended borehole. The collimated beam size was measured to be 0.6-mm diameter by measuring coincidence count rate as we scanned off the edge of a 0.8-mm-thick LYSO scintillator.

The calibration beam setup for MFb did not use a bore hole collimator, but instead placed the 4-by-4-by-20 mm³ LYSO coincidence detector a distance 10 cm away, also resulting in a similar beam size (~0.65 mm).

The 0.6-mm-diameter 511-keV gamma-ray beam was aimed at one crystal element (Left or Right) and the responses of the two photodetectors (PD1 and PD2) were read out for 5,000 to 10,000 events (Figure 7). Except for MFb, charge-integrated signals were acquired with a VME system triggered by NIHM electronics (Figure 8). For the MFb sample, signals were acquired with an Ortec AD811 ADC instead (triggering remained the same). These measurements were repeated at each depth (step sizes indicated in Figures 12–19) for each of the dMiCE test crystals in Table 1. For crystals 1c, 2a, 2b, and MFb, this process was repeated for both Left and Right crystals of the dMiCE pair. For 1a, 1b, and MFa, this process was only done for the Right crystal.

D. Filtering

We use only photopeak events for calibration and evaluation. For calibration of detector response statistics, photopeak events are identified in three steps (Figure 9). First, to reject some inter-crystal scatter, we keep only events where the gain-corrected signal of the targeted crystal is more than its neighbor's. Second, to eliminate Compton escape events and 1274-keV down scatter, we consider only events within a $\pm 17\%$ energy window about the photopeak of the gain-corrected sum signal for PD1 and PD2. As a final step in rejecting scatter, we keep only events within a 10% contour about the peak count-density of the joint signal distribution for PD1 and PD2 (i.e. the full-width at tenth-max contour).

To test event-positioning performance, we only use the last two steps described above. In other words, events are not filtered based on which channel has the larger signal.

E. Positioning

Photopeak events of a separate test-data set are positioned by maximum likelihood (ML) estimation [4]. For this purpose, we assume signals for PD1 and PD2 (g_1, g_2) for a fixed interaction position, $\mathbf{r}$, and energy, E , result from an independent bivariate normal distribution, $\mathcal{N}(g_1, g_2 | \mathbf{r}, E)$. The mean and variance of the filtered calibration data (e.g., from the projected distribution in Figure 9) are computed for each beam position. To reduce uncertainty in the calibrated variance, we smooth the measured variance as a function of depth using a local quadratic fit with span 13. In cases where the calibration beam step size is greater than 1 mm, these mean and variance lookup tables are interpolated using a bicubic spline. We then use the resulting maps of mean and variance versus position (e.g., Figures 10 and 11) to compute a likelihood map for each event, from which we find the event's ML position estimate:

$$\hat{\mathbf{r}} = \underset{\mathbf{r}}{\operatorname{argmax}} \mathcal{N}(g_1, g_2 | \mathbf{r}, E).$$

F. Resolution

The depth estimate distributions are not normally distributed. Therefore, we choose to compute depth resolution as 2.35 times the standard deviation of the ensemble distribution of event position estimates. This measure of resolution is adequate for comparing DOI-positioning performance of different dMiCE crystals. Performance of crystal identification is not fully examined in this work. However, we note that in Figure 9, the photopeak events of the bivariate signal distribution is well separated for events interacting in the Left and Right halves of the dMiCE crystal.

III. Results

Mean and standard deviation of detector response to photopeak events are reported versus interaction depth for seven crystals types in Figures 12–19. Only the right side of the crystal was calibrated in Figures 12–15, while both sides were examined in the remaining crystals.

Figure 12 shows detector response for three crystals without any interface (prior to SSLE); Due to a slight mismatch in gain and differences in solid angle of the two photodetectors we see on a slight difference between the response of the two photodetectors; depth sensitivity only enters as a slight increase in total light collected for interactions closer to the photodetectors. Figure 12 also shows excellent consistency in the total and fraction of light collected by PD1 and PD2 for these three samples. This verifies consistent coupling and alignment of the crystal onto the photodetectors.

In Figure 13, we see that manually coupling a pair of crystals with mirror film and optical grease resulted in fairly good optical isolation of the two photodetectors. However, this interface also resulted in very poor depth dependence since there was inadequate light sharing at the optically coupled end of the interface where optical grease was used. Poor optical coupling here is due to a mismatch of refractive index (1.81 for LYSO and 1.46 for the optical grease).

In Figure 19, we see that changing the coupling medium from 1.46-index optical grease to a high-index optical adhesive (Meltmount 1.705) resulted in getting significantly better depth dependence on light sharing across the interface. On the end where Meltmount was used (depth 0–4 mm), the mean responses of PD1 and PD2 are more closely matched than at the opposite end where mirror film isolates the crystals.

Figure 14 and 15 also show a marked improvement in the depth dependence of light sharing across the shaped 1-layer SSLE interface. In Figure 16, we see a further increase in this depth dependence by changing the 1-layer SSLE grid point spacing from 140 nm to 120 nm.

Finally, in Figures 17 and 18 we see that 2-layer SSLE reinforces isolation of scintillation light near the photosensor; the gap in mean response of PD1 and PD2 widens near the photosensor. We note that in Figure 17 the mean response of PD2 when the beam is aimed at the left crystal differs significantly from PD1 when beam is to the right; it also differs from the response of PD2 in the equivalent configuration of Figure 18. We think that in the calibration of this one crystal, there was a slight misalignment of the SSLE interface with the gap between PD1 and PD2. If the interface is offset to one side, we would expect an asymmetric light sharing by the photodetectors for interactions on the left and right sides of the interface.

In comparing pre-SSLE (Figure 12) and post-SSLE treatment (Figures 14–16) of crystals 1a, 1b and 1c we observe a significant increase in light loss with depth. This may be due in part to absorption at the SSLE interface. However, if this increased light loss were due completely to absorption of light at the SSLE interface, we would expect even more light loss in the 2-layer SSLE interface. However, the light loss in the 2-layer SSLE appears similar to the 1-layer SSLE. Therefore, we think this increased light loss in all SSLE samples occurs in part to penetration of the Teflon wrapped perimeter; with the added SSLE interface, the average number of reflections of scintillation light from the Teflon (before detection) increases. This effect, which can be reproduced in optical ray-trace simulation [5], is greater when the gamma interaction is farther from the photodetectors.

With these calibrated detector response maps, we find the ML estimate of interaction depth for an ensemble of 5,000 to 10,000 photopeak events at each depth. Estimate distributions are shown for five depths for each dMiCE sample in Figures 20–25. In each case, we find there to be a pile up of the estimates near the edge for beam positions at far end, away from the photodetector ($\text{DOI} < 6\text{-mm}$). This pileup is due to the relatively large signal variance compared to the change in response with depth over this end of the crystal. Therefore, so that we can compare depth-positioning performance of different dMiCE crystals, we compute resolution as 2.35 times the standard deviation of the depth-estimate distribution. A summary of this resolution measure versus beam depth is given for each of the test crystals in Figure 26. A summary of depth-weighted resolution is given in Table 2 for front-sided and back-sided readout for each dMiCE type examined.

Discussion

SSLE was used to shape the light response function of a dMiCE photodetector pair. The resulting depth resolution for a 2-layer SSLE interface (better than 4-mm) was comparable to that of a conventional crystal pair formed with shaped mirror-film and a high-index (1.7) optical adhesive.

Depth sensitivity of this SSLE dMiCE detector comes in part from better light coupling near the end opposite the photodetectors and adequate opacity of the SSLE interface. However, it also results from depth dependence of total light detected. Unfortunately, depth dependent light collection convolutes the tasks of resolving depth and resolving energy. We will therefore need to address this light loss. If light is penetrating the perimeter of these narrow (1.4:20 aspect ratio) SSLE-dMiCE crystals, then we may need a different reflector; alternatively we may need to collect light in the photodetectors of adjacent dMiCE crystal for energy estimation. We also need to take a closer look at if light is being absorbed at the SSLE interface.

In this work, we also observed that aligning the SSLE interface between the two photodetectors is very important. Otherwise light may directly illuminate the abutted photodetector rather than going around the optical barrier. For this purpose, we might consider a wider SSLE interface near the photodetector end of the crystal.

Finally, to increase depth sensitivity of an SSLE-dMiCE crystal further, we will be examining higher point-density interfaces with the improved SSLE system in development shown in Figure 4. We are unable to increase point density further using our current SSLE system without causing macroscopic fractures, compromising crystal integrity and affecting light distribution in un-planned ways.

Acknowledgments

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Figure 1.

Conventional dMiCE design reported in prior work [1]. Two $2 \times 2 \times 20\text{-mm}^3$ crystals were re-joined with optical adhesive and a shaped mirror film was used to control light sharing as a function of interaction depth. The non-shared crystal surfaces are wrapped in Teflon. The crystal surface in the optically coupled region was roughened with 600-grit sandpaper.

Figure 2.

Left is shown the surplus first-generation sub-surface laser engraving system by Crystalix Evolution GmbH used for this work. A confocal microscope image of point defects produced with this system exhibit significant collateral damage, as shown to the right.

Figure 3.

Two SSLE dMiCE crystals engraved by the system in Figure 2. Their interfaces are one layer of SSLE points on a 120- μm -grid spacing.

Figure 4.

Left is shown our next generation sub-surface laser engraving system by Crystalix Evolution GmbH. A confocal microscope image of point defects produced by this system using optimized laser-pulse profile is at the right.

Figure 5.

(a) Custom photodetector array planned for reading out 32 dMiCE crystal pairs; (b) The photodetector pair used for testing dMiCE performance are 3-by-3 mm² active area.

Figure 6.
Photograph of calibration setup viewed from above

Figure 7.
Diagram of calibration setup.

Figure 8.
Signal acquisition setup

Figure 9.

Example of event filtering for two beam positions (top) 1-mm DOI, and (bottom) 19-mm DOI. We show the beam position (left) and bivariate signal distribution (right). Univariate signal histograms of the contour-filtered data projected to the right (PD1) and top (PD2).

Figure 10.

Mean response to photopeak events for both photodetectors, PD1 and PD2, of sample-2a dMiCE are reported as a function of interaction depth for when the interactions occur in the Left or Right half of this dMiCE crystal

Figure 11.

Response variance to photopeak events for both photodetectors, PD1 and PD2, of sample-2a dMiCE are reported as a function of interaction depth for when interactions occur in the Left or Right half of this dMiCE crystal. In this case, we expect the uncertainty on the response variance of interactions on the Right side to be smaller by a factor of two since we collected four times as many events on the right side than on the left side. Since we expect response variance to be a smooth function of interaction depth, we perform a local quadratic fit (span 13) to reduce calibration noise.

Figure 12.

Pre-SSLE detector response statistics for photopeak events in dMiCE crystals 1a, 1b, and 1c: mean (line) and ± 1 std. deviation (error bars)

Figure 13.
Sample MFa (mirror film and optical grease) detector response statistics for photopeak events: mean (line) and ± 1 std. deviation (error bars)

Figure 14.

Sample 1a (1-layer SSLE, 140-nm grid) detector response statistics for photopeak events: mean (line) and ± 1 std. deviation (error bars)

Figure 15.
Sample 1b (1-layer SSLE, 140-nm grid) detector response statistics for photopeak events:
mean (line) and ± 1 std. deviation (error bars)

Figure 16.

Sample 1c (1-layer SSLE, 120-nm grid) detector response statistics for photopeak events: mean (line) and ± 1 std. deviation (error bars)

Figure 17.

Sample 2a (2-layer SSLE, 120-nm grid) detector response statistics for photopeak events: mean (line) and ± 1 std. deviation (error bars)

Figure 18.

Sample 2b (2-layer SSLE, 120-nm grid) detector response statistics for photopeak events: mean (line) and ± 1 std. deviation (error bars)

Figure 19.

Sample MFb (mirror film and Meltmount) detector response statistics for photopeak events: mean (line) and ± 1 std. deviation (error bars). As noted previously, the acquisition electronics for MFb were different than the rest of the crystals examined.

Figure 20.
Depth-estimate distribution for five beam positions in sample 1a (1-layer SSLE, 140-nm grid)

Figure 21.
Depth-estimate distribution for five beam positions in sample 1b (1-layer SSLE, 140-nm grid)

Figure 22.
Depth-estimate distribution for five beam positions in sample 1c (1-layer SSLE, 120-nm grid)

Figure 23.
Depth-estimate distribution for five beam positions in sample 2a (2-layer SSLE, 120-nm grid)

Figure 24.
Depth-estimate distribution for five beam positions in sample 2b (2-layer SSLE, 120-nm grid)

Figure 25.

Depth-estimate distribution for five beam positions in sample MFb (mirror film and Meltmount)

Figure 26.
Summary of DOI position resolution versus depth of interaction for each of the dMiCE crystal treatments considered.

Table 1

Description of tested dMiCE crystal samples

Sample ID	L × W [mm]	Interface Description	SSLE step [μm]
1a	1.4×2.9	1 SSLE layer (see Figure 3)	140
1b	1.4×2.9	1 SSLE layer (see Figure 3)	140
1c	1.4×2.9	1 SSLE layer	120
2a	1.4×2.9	2 SSLE layers (160μm apart)	120
2b	1.4×2.9	2 SSLE layers (160μm apart)	120
MFa	Two 1.4×2.9	BC630 grease, 18mm VM2000 on 1.4×20 mm ² side	n/a
MFb	Two 2.0×2.0	Meltmount & 18mm VM2000 on 2×20 mm ² side (Figure 1)	n/a

Table 2

Summary of depth-weighted resolution for each crystal design

dMiCE interface type	Depth-weighted resolution [mm]	
	Front-sided	Back-sided readout
1-layer SSLE (avg. of 1a,b,c)	4.9	5.6
2-layer SSLE (avg. 2a & 2b)	3.4	3.9
Mirror film & optical grease (MFa)	9.9	10.5
Mirror film & Meltmount 1.7 (MFb)	3.6	4.2
No interface	15	16