

Development of a SiPM based gamma-ray imager using a $\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Ce}$ (GAGG:Ce) scintillator array

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Abstract– In this study we present the performance evaluation of a 6×6 $\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Ce}$ (GAGG:Ce) pixellated scintillator with $2 \times 2 \times 5 \text{mm}^3$ crystal size elements, coupled to a silicon photomultiplier array (ArraySL-4). Evaluation was carried out with low energy isotopes i.e. ^{57}Co and $^{99\text{m}}\text{Tc}$. A symmetric resistive charge division matrix was used reducing array's 16 outputs to 4 position signals. A Field Programmable Gate Array (FPGA) Spartan 6 LX16 was used for triggering and signal processing of the signal pulses acquired using a free running sampling technique. Raw images of the crystals maps were acquired. The mean energy resolution at 140keV and 122.1 keV was $16.1 \pm 0.52\%$ and $18.1 \pm 0.64\%$ respectively, and the peak to valley ratio was found equal to 17.7 ± 2.7 . Comparative measurements of two $3 \times 3 \times 5 \text{mm}^3$ CsI:Tl and GAGG:Ce scintillators of same thickness are also presented. All measurements were performed at room temperature $\sim 25^\circ\text{C}$, without additional cooling. According to our knowledge this is the first time that the new developed GAGG:Ce scintillator array has been evaluated at low energies.

I. INTRODUCTION

Ce doped Gadolinium Aluminum Gallium Garnet ($\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Ce}$ or GAGG:Ce) is the most recent developed single crystal scintillator with good light yield (46000 ph/MeV) [1]. GAGG:Ce crystals have a light-yellowish color, with peak emission light at 530nm. Moreover, GAGG:Ce does not contain natural radioactivity, since it does not use Lu. The scintillators containing Lu, such as LSO, LYSO and LuAG introduce problems from the simultaneously beta-gamma emissions of natural Lu-176 [2]. The production of Ce doped Gadolinium Aluminum Gallium Garnet prepared by the Czochralski method in bulk single crystal form, has been previously reported [3]. GAGG:Ce is non hygroscopic,

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which is an advantage compared with CsI:Tl and NaI:Tl scintillator crystals - mainly used in SPECT applications - with faster response, leading to higher count rates capability. The density of GAGG:Ce is 6.63 g/cm^3 , which is higher than CsI:Tl and NaI:Tl (4.5 and 3.67 respectively) and with effective atomic number equal to 54.4 [1-4]. NaI:Tl as well as CsI:Tl are the gold standard scintillator detectors for SPECT imaging emitting scintillation light in the blue and green region of the spectrum respectively. We list the properties of the latter scintillators in Table 1 for comparison.

Silicon Photomultipliers (SiPMs), also known as multi-pixel photon counters (MPPCs) or solid-state photomultipliers (SSPMs), present an alternative solution, which to a large extent combines the advantages of PMTs and APDs [5]. They have high gain $\sim 10^6$ (similar to PMTs) and operate at low bias voltages ($< 80\text{V}$) [5]. They are relatively insensitive to magnetic fields and thus are good candidates for MR combined applications [6-9]. Previous studies using a monolithic MPPC array with pixellated GAGG:Ce crystals were reported achieving sub millimeter spatial resolution for PET applications [10]. Moreover, measurements of GAGG:Ce scintillator regarding emission spectra, decay time, light output, non-proportionality, energy and time resolution were reported recently by J. Iwanowska et al. [1].

In this study, we present the results of the SensL ArraySL-4 (4×4 element array of $3 \times 3 \text{mm}^2$ SiPMs) optical detector coupled to a 6×6 GAGG:Ce scintillator array, with $2 \times 2 \times 5 \text{mm}^3$ crystal size elements. Evaluation was carried out with $^{99\text{m}}\text{Tc}$ and ^{57}Co . A symmetric resistive voltage division matrix was applied, which reduces the 16 outputs of the array to 4 position signals [11-14]. Experimental evaluation in terms of energy resolution and peak to valley ratio are reported. Moreover, we acquired energy spectra from a single CsI:Tl $3 \times 3 \times 5 \text{mm}^3$ scintillator crystal - positioned at the one central pad of field of view of the SiPM array - and we compared the results with a single GAGG:Ce scintillator of same dimensions. All measurements were performed at room temperature $\sim 25^\circ\text{C}$, without additional cooling circuit.

II. MATERIALS AND METHODS

GAGG:Ce scintillator array as well as the GAGG:Ce single crystal with dimensions of $3 \times 3 \times 5 \text{mm}^3$ used in this study were purchased by Furukawa Co Ltd [15]. The 6×6 GAGG:Ce scintillator array has $2 \times 2 \times 5 \text{mm}^3$ crystal size elements with

pitch 2.1mm. The reflector material used in the array is BaSO₄ with 0.1mm thickness. The 3x3x5mm³ CsI:Tl scintillator sample was purchased by Hilger Crystals [16]. All scintillators' surfaces were polished. Both single scintillator samples were wrapped with white Teflon tape and coupled to the SiPM array using optical grease (BC-630).

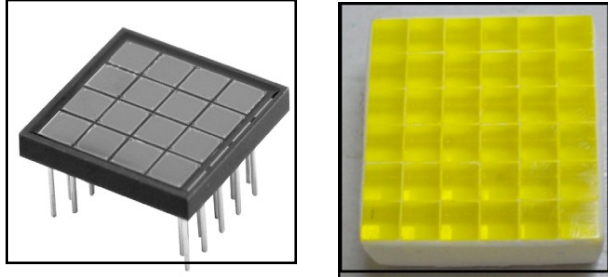


Fig. 1 (Left) ArraySL-4 silicon photomultiplier 4x4 array, (Right) 6x6 crystals GAGG:Ce scintillator array.

TABLE I. CHARACTERISTICS OF SCINTILLATOR DETECTORS

Scintillator	Density (g.cm ⁻³)	Hygroscopicity	Light yield (ph/MeV)	Decay time (ns)	Emission peak (nm)
GAGG:Ce	6.63	No	46000	~90	530
NaI:Tl	3.67	Yes	41000	230	410
CsI:Tl	4.5	Yes	66000	800	550
LSO :Ce	7.4	No	26 000	40	420
LYSO:Ce	7.1	No	30 000	45	420
GSO:Ce	6.71	No	8 000	60	440
LuAG:Pr	6.73	No	20 000	20	310

The SensL's scalable silicon photomultiplier array (ArraySL-4) is a commercially available, solid-state, large array detector based on silicon photomultiplier technology [17]. It consists of 16 pixel elements covering an active area of 13.4mm². Each pixel has 4774 square microcells connected in parallel, with individual cell side equal to 35um. The ArraySL-4 is sensitive to visible light in the range of 400nm to 850nm with peak photon detection efficiency (PDE) 14% at 500nm [17]. PDE value referred includes crosstalks and afterpulses. The particular ArraySL-4 detector works properly at a low bias voltage of +29.3 V as it is recommended by the manufacturer. According to the SensL Company the SL family silicon photomultiplier detectors have four times higher signal-to-noise ratio than previous generation SensL products and better uniformity. The ArraySL-4 output uniformity is ±10%. In comparison, photomultiplier tubes have ±33% output uniformity.

The 16 output signals of the SiPM array are further reduced to 4 position signals through a two-stage charge division resistive network (Charge-SCD resistive readout). First, the incoming charges from the 4x4 SiPM array are

equally split into X and Y directions using a symmetric 2D decoupling resistive matrix, which results in 16 readout channels reducing to 8 channels (4 rows and 4 columns). Secondly, the 8 readout channels are individually amplified and shaped. Then the 8 readout channels are further reduced to 4 outputs (X_a, X_b, Y_c, Y_d) using a resistive division network of amplitude weighting resistors. The centroid position (X, Y) of the incident light pulse distribution is finally calculated using Anger's equations (1). A summed signal from the four position signals was used to provide the energy (2).

$$X = \frac{X_a - X_b}{X_a + X_b}, \quad Y = \frac{Y_c - Y_d}{Y_c + Y_d} \quad (1)$$

$$E = X_a + X_b + Y_c + Y_d \quad (2)$$

More details about the resistive network that was used can be found in our previous study in [11]. The 4 position signals (X_a, X_b, Y_c and Y_d) were amplified and then digitized using a free running ADC [18-19]. The amplifiers shape the input signals taking into account the ADC sampling rate. A FPGA (Spartan 6 LX16) was used for triggering and signal processing of the pulses. Data were transferred to a standard PC via ethernet link.

III. RESULTS AND DISCUSSION

A raw image and the horizontal profile of one raw of the 6x6 GAGG:Ce scintillator array are shown in figure 2. The mean peak to valleys ratio is 17.7 with a standard deviation (std) equal to 2.7.

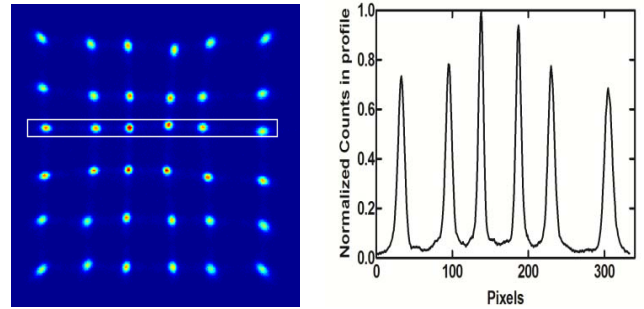


Fig. 2 Raw image of the 6x6 GAGG:Ce scintillator array and the horizontal profile of the scintillator elements. Scintillator array optically coupled to the SiPM entrance window only with optical grease (BC-630).

In figure 3, the energy resolution values of the 36 scintillator elements (2x2x5mm³) of the GAGG:Ce array under ^{99m}Tc and ⁵⁷Co irradiation are illustrated. The mean energy resolution for the 140keV and 122.1 keV excitation was calculated equal to 16.1% (std=0.52) and 18.1% (std=0.64) respectively, using Gaussian fit within a +/-10% energy window centered on the photopeak.

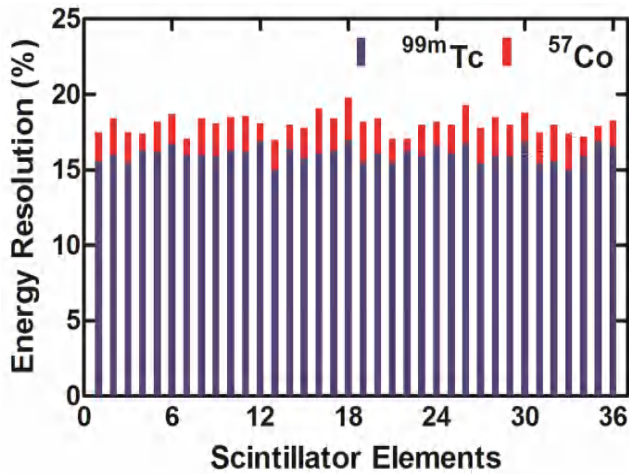


Fig. 3 Energy resolution values of the 36 scintillator elements ($2 \times 2 \times 5 \text{ mm}^3$) of the GAGG:Ce array under $^{99\text{m}}\text{Tc}$ and ^{57}Co irradiation. The crystals 1 is positioned at the left up corner while the 36 at the bottom down.

Energy spectra from a single $3 \times 3 \times 5 \text{ mm}^3$ CsI:Tl and GAGG:Ce scintillator single crystals - positioned at one pad at the center of the field of view of the SiPM array are shown in figure 4. The mean energy resolution for the CsI:Tl and GAGG:Ce was calculated equal to 23.1% and 18.3% respectively under 140keV irradiation. GAGG:Ce scintillator is characterized by a higher light output signal, (photopeak centroid at 479 channel of the Multichannel analyzer) compared to the CsI:Tl (photopeak centroid at 267 channel).

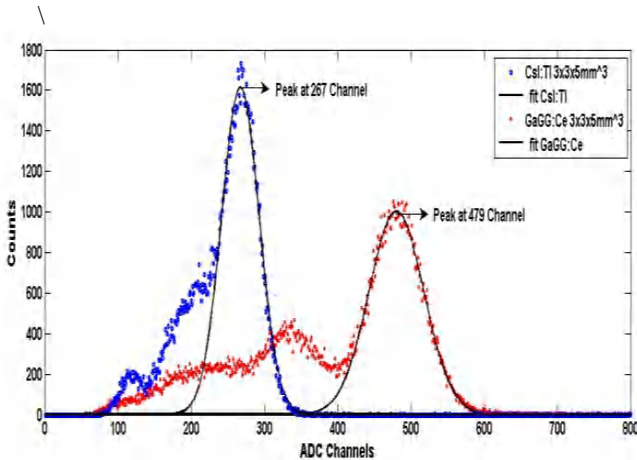


Fig. 4 Energy spectra from a single $3 \times 3 \times 5 \text{ mm}^3$ CsI:Tl and GAGG:Ce scintillator single crystals - positioned at the one central pad of field of view of the SiPM array. The mean energy resolution for the CsI:Tl and GAGG:Ce was calculated equal to 23.1% and 18.3% @140keV respectively.

IV. CONCLUSION

The acquired raw images of the GAGG:Ce crystal array show a clear visualization all (6x6) discrete scintillator elements. The measurements performed with GAGG:Ce scintillator showed that this scintillator is characterized by a higher light output signal, compared to CsI:Tl. Taking also into account its very fast response and its higher detection efficiency compared with NaI:Tl and CsI:Tl, GAGG:Ce could

be considered a *scintillator of choice* for application in detectors for imaging $^{99\text{m}}\text{Tc}$ based radiopharmaceuticals.

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