Evaluation of a SiPM array coupled to a Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce (GAGG:Ce) discrete scintillator

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ABSTRACT

Purpose: In this study, we present the results of the evaluation of the SensL ArraySL-4 photo-detector, coupled to a 6 × 6 GAGG:Ce scintillator array, with 2 × 2 × 5 mm$^3$ crystal size elements for possible applications in medical imaging detectors with focus on PET applications. Experimental evaluation was carried out with $^{22}$Na and $^{137}$Cs radioactive sources and the parameters studied were energy resolution and peak to valley ratio.

Methods: ArraySL-4 is a commercially available, 4 × 4 array detector covering an active area of 13.4 mm$^2$. The GAGG:Ce scintillator array used in this study has 0.1 mm thickness BaSO$_4$ reflector material between the crystal elements. A symmetric resistive voltage division matrix was applied, which reduces the 16 outputs of the array to 4 position signals. A Field Programmable Gate Array was used for triggering and digital processing of the signal pulses acquired using free running Analog to Digital Converters.

Results: Raw images and horizontal profiles of the 6 × 6 GAGG:Ce scintillator array produced under 511 keV and 662 keV excitation are illustrated. Moreover, the energy spectra obtained with $^{22}$Na and $^{137}$Cs radioactive sources from a single 2 × 2 × 5 mm$^3$ GAGG:Ce scintillator are shown. The peak to valley ratio and the mean energy resolution values are reported.

Conclusions: The acquired raw image of the GAGG:Ce crystal array under 511 keV excitation shows a clear visualization of all discrete scintillator elements with a mean peak to valley ratio equal to 40. The mean energy resolution was measured equal to 10.5% and 9% respectively under 511 keV and 662 keV irradiation.

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Introduction

In most X-ray and gamma-ray applications inorganic scintillators are employed as radiation in light converters [1,2]. These applications demand scintillators with high light yield, good energy resolution, high effective atomic number, fast scintillation response and chemical stability [3]. A recently developed mixed scintillator crystal with high density, fast scintillation response and high light yield is the Ce doped Gadolinium Aluminum Gallium Garnet (Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce or GAGG:Ce) [4]. GAGG:Ce is non hygroscopic, which is an advantage compared with LaBr$_3$:Ce, LaCl$_3$:Ce, CsI:TI, CsI:Na and NaI:Tl scintillator crystals. GAGG:Ce scintillators emit a light-yellowish color light and its effective atomic number is equal to 54.4 [5,6]. We list the properties of the latter scintillators in Table 1 for comparison.

Moreover, GAGG:Ce does not contain natural radioactivity, since it does not uses Lu. The scintillators containing Lu, such as LSO:Ce, LYSO:Ce, LGSO:Ce and LuAG:Pr introduce problems from the simultaneously beta-gamma emissions of natural Lu-176 that affect the minimum detectable activity limits of a system [7]. On the other hand a drawback of the GAGG:Ce scintillator is its magnetic non compatibility due to the presence of strongly magnetic Gd (used for MR contrast agent in MRI) that produce significant artifacts and distortion on the MRI imaging [8], which does not allow its exploitation in MR-compatible systems.

Silicon photomultiplier arrays (SiPMs) are becoming detectors of choice for compact, as well as whole body PET and SPECT systems due to their small size and attractive characteristics [9]. They have high gain (similar to that of PMTs) and are operated at low bias voltages (<80 V) [10]. They are relatively insensitive to magnetic fields and thus are good candidates for MR combined applications.
In addition, they show excellent timing resolution (below 200 ps) [11,12], which makes them suitable for Time-of-Flight (ToF) PET applications [13]. Moreover, SiPMs achieve recently high values of photon detection efficiency (PDE) and have lower cost than PMTs. On the other hand, SiPMs have bigger dark count rate than PMTs and require careful temperature control for stable operation because their gain is sensitive to temperature variations. However, their technology continuously evolves and many studies are reported where cooling is not required to achieve adequate signal-to-noise levels [7,14].

The production of Ce doped Gadolinium Aluminum Gallium Garnet, has been previously reported [5]. Several studies of energy resolution and timing performance of GAGG crystals readout by a variety of photon detection technologies (APD, SiPM, PMT, MPPC, PIN diode) have shown that this crystal is promising in medical imaging and gamma spectroscopy applications [7,15,16]. Moreover a development of sub millimeter GAGG block detector using 0.4 mm GAGG pixels was reported for PET and SPECT applications [17]. Very recently, an application of thin GAGG scintillator plates (1 mm thick) was published for the construction of a compact well counter used for radio cesium concentration measurements [18]. Moreover alpha particle detection with GAGG scintillator crystals and a handy Compton camera using a 3D position-sensitive GAGG scintillator matrix were reported for security applications and radiation monitoring in nuclear fuel facilities [19].

In previous study of our group – using the same detector module materials – we evaluated a $2 \times 2 \times 5$ mm$^3$ GAGG:Ce pixelated array ($6 \times 6$ scintillator pixels) based on SensL ArraySL-4 (4 $\times$ 4 element array of $3 \times 3$ mm$^2$ silicon photomultipliers) photo receptor [14] under low energy isotopes ($^{57}$Co and $^{99}$mTc) for SPECT applications. In this study, we present the results of the same detector module for possible PET applications. Experimental evaluation was carried out with $^{22}$Na and $^{137}$Cs radioactive sources in terms of energy resolution and peak to valley ratio.

### Materials and methods

GAGG:Ce scintillator array used in this study was purchased by Furukawa Co Ltd. The reflector material used in the array is BaSO$_4$ with 0.1 mm thickness. The coupling material used between the scintillator and the entrance window of the SiPM array was BC-630 optical grease.

### SiPM detector characteristics

The ArraySL-4 SensL’s scalable silicon photomultiplier array is an older version commercially available, solid-state, large array detector based on silicon photomultiplier technology [20]. It consists of 16 pixel elements covering an active area of 13.4 mm$^2$.

### Electronics and data acquisition system

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) [21]. First, the incoming charges from the 4 $\times$ 4 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 position signals (Xa, Xb, Yc, Yd) by a resistive division network of weighting resistors. The centroid position (X, Y) of the incident light pulse distribution is finally calculated using Anger’s equations. A summed signal from the four position signals was used to provide the energy of each detected photon. More details about the resistive network that was used can be found in a previous study of our group [22]. The 4 position signals (Xa, Xb, Yc and Yd) were amplified and then digitized using free running ADCs (12-Bit Octal-Channel, 65MSPS ADCs of Texas Instruments). The sampling rate was chosen to be equal to 50 MHz, taking into account the amplified analog signals rise and decay times. A Field Programmable Gate Array (FPGA) Spartan 6 LX150T was used for triggering and processing of the four digitized position signals. Data were transferred to a standard PC via Ethernet link. The data acquisition system architecture is described in Ref. [23] and was implemented in the aforementioned FPGA, which has more

### Table 1

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density (g cm$^{-3}$)</th>
<th>Hygro-scopcity</th>
<th>Light yield (ph/MeV)</th>
<th>Decay time (ns)</th>
<th>Emission peak (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAGG:Ce</td>
<td>6.63</td>
<td>No</td>
<td>46,000</td>
<td>90</td>
<td>520</td>
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<tr>
<td>NaI:Tl</td>
<td>3.67</td>
<td>Yes</td>
<td>41,000</td>
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<td>410</td>
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<tr>
<td>CsI:Tl</td>
<td>4.5</td>
<td>Yes</td>
<td>66,000</td>
<td>800</td>
<td>550</td>
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<tr>
<td>LSNO:Ce</td>
<td>7.4</td>
<td>No</td>
<td>26,000</td>
<td>40</td>
<td>420</td>
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<tr>
<td>LYSO:Ce</td>
<td>7.1</td>
<td>No</td>
<td>30,000</td>
<td>45</td>
<td>420</td>
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<tr>
<td>LGSO:Ce</td>
<td>7.0</td>
<td>No</td>
<td>28,000</td>
<td>45</td>
<td>430</td>
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<tr>
<td>GSO:Ce</td>
<td>6.71</td>
<td>No</td>
<td>8000</td>
<td>60</td>
<td>440</td>
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<tr>
<td>LuAG:Pr</td>
<td>6.73</td>
<td>No</td>
<td>20,000</td>
<td>20</td>
<td>310</td>
</tr>
<tr>
<td>LaBr$_3$:Ce</td>
<td>5.08</td>
<td>Yes</td>
<td>63,000</td>
<td>16</td>
<td>380</td>
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<tr>
<td>LaCl$_3$:Ce</td>
<td>3.85</td>
<td>Yes</td>
<td>49,000</td>
<td>28</td>
<td>350</td>
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</table>

### Table 2

<table>
<thead>
<tr>
<th>SiPM array characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company Name</td>
</tr>
<tr>
<td>Model</td>
</tr>
<tr>
<td>Number of pixels</td>
</tr>
<tr>
<td>Active area</td>
</tr>
<tr>
<td>Pixel size</td>
</tr>
<tr>
<td>Cell size</td>
</tr>
<tr>
<td>Cells per pixel</td>
</tr>
<tr>
<td>Bias Voltage</td>
</tr>
<tr>
<td>Gain</td>
</tr>
<tr>
<td>Photon detection efficiency at 500 nm$^2$</td>
</tr>
</tbody>
</table>

* The PDE referred value includes crosstalks and after pulses.
available logic resources compared to the one used in Ref. [23] and can be used to deserialize ADC data at 50 MHz sampling rate.

Experimental measurements

All measurements were conducted at stable room temperature in a black box. The radioactive sources that were used in the experiments were $^{22}$Na and $^{137}$Cs, with radioactivity of $-1 \mu$Ci. The mean peak to valleys (P/V) ratio, as well as, their relative standard deviations (std), were calculated from six horizontal and six vertical raw profiles. The maximum gray scale value in the profile was normalized to unity. The mean energy resolution value of the detector was determined from full width at half maximum values of the 36 individual photopeaks acquired using Gaussian fit within a $\pm 10\%$ energy window. The corresponding standard deviation value, is reported. The energy spectra were normalized in the maximum value.

Results and discussion

A raw image and the horizontal profile of one central raw of the $6 \times 6$ GAGG:Ce scintillator array produced under $511$ keV excitation are shown in Fig. 1. The mean peak to valleys ratio is 40 (std $= 8.2$). GAGG:Ce based detector presents higher peak to valleys ratio from that measured previously by our group [24] with the same optical detector coupled by a BGO scintillator array with the same crystal size elements (mean peak to valleys ratio for BGO equal to 15.4).

Energy spectra obtained with two different radioactive sources from a single $2 \times 2 \times 5$ mm$^3$ GAGG:Ce scintillator element (red square on raw image) are shown in Fig. 2, normalized at the maximum value. The mean energy resolution for the GAGG:Ce array was calculated equal to 10.5% (std $= 0.44$) and 9% (std $= 0.63$) under $511$ keV and $662$ keV irradiation respectively using Gaussian fit within a $\pm 10\%$ energy window centered on the photopeak. Those values are very similar with those presented in literature with MPPC detector arrays [15,16].

Discussion – conclusion

The acquired raw image of the GAGG:Ce crystal array under $511$ keV excitation shows a clear visualization of all ($6 \times 6$) discrete scintillator elements with a mean peak to valley ratio equal to 40. The mean energy resolution was measured equal to 10.5% and 9% under $511$ keV and $662$ keV irradiation respectively. Those values are comparable to the Lu based PET detectors, which have been presented in literature [25]. Taking into account the results conducted in a previous study of our group [14] under low energy isotopes i.e. $^{57}$Co and $^{99m}$Tc (for SPECT applications) using the same detector module materials, (mean energy resolution equal to 16.1 $\pm 0.52\%$ at 140 keV and 18.1 $\pm 0.64\%$ at 122.1 keV with high peak to valley ratio above 17) a SPECT/PET hybrid detector could be a possible interesting application using the aforementioned GAGG/SiPM array detector. In such a dual SPECT/PET detector module, proper mechanical insert of the collimator, as well as the adjustment of the SiPMs array bias voltage and the gain amplification of the position signals have to be properly controlled to allow transition from PET to SPECT mode.

An ongoing work of our group includes the evaluation – under $^{99m}$Tc and $^{22}$Na excitation – of the GAGG discrete scintillator array with smaller pixel size equal to $1 \times 1 \times 10$ mm$^3$ in order to obtain better spatial resolution properties. Moreover, the optimization of the optical coupling among the scintillation crystal array and the SiPM entrance window and the assessment on larger blocks constructed by two or more ArraySL-4 detectors in an array is still under investigation.

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