Performance characteristics of a personal gamma spectrometer based on a SiPM array for radiation monitoring applications

E Kefalidis\textsuperscript{1}, I Kandarakis\textsuperscript{1,2} and S David\textsuperscript{1,2}

\textsuperscript{1}Department of Biomedical Engineering, Technological Educational Institute of Athens, Athens, Greece
\textsuperscript{2}Radiation Physics, Materials Technology and Biomedical Imaging Laboratory, Department of Biomedical Engineering, Technological Educational Institute of Athens, Egaleo, 12210 Athens, Greece

Corresponding Author: S David, sdavid@teiath.gr

Keywords: Radiation monitoring, SiPM, GAGG:Ce, Compact Spectrometers

Abstract. Due to the increased radiation pollution in the environment as a result of the often nuclear accidents taking place around the world, the need for efficient, reliable, smart and handheld radiation measurement systems has been born especially in daily routine. In this study it is evaluated the angular response of two crystal non-pixelated Gd\textsubscript{3}Al\textsubscript{2}Ga\textsubscript{3}O\textsubscript{12}:Ce (GAGG:Ce) scintillators with dimensions at 10x10x10mm\textsuperscript{3} \& 10x10x20mm\textsuperscript{3} under \textsuperscript{137}Cs isotope emitting at 662 keV coupled to a 4x4 discrete silicon photomultiplier array (SiPM). A symmetric resistive voltage division matrix was applied reducing the array 16 outputs to 4 analog position signals which digitized by a 4 Channel 12 bit 250 MS/s desktop waveform digitizer. The number of the evaluated angles set at 5 (0\degree, 45\degree, 90\degree, 135\degree, 180\degree) and a variety of measured values are presented (energy resolution, sensitivity, figure of merit etc). The encouraging results such as energy resolution about 9\% and figure of merit equal to 4.11 for 10x10x10mm\textsuperscript{3} and 4.43 for 10x10x20mm\textsuperscript{3} crystal, prove that this system could build up to a compact radiation sensor for integration into mobile applications.

1. Introduction

Nuclear energy penetrates in science applications constantly over the year. Power production, military equipment and medicine are some of the most significant sectors which develop radioactivity technologies rapidly under huge government investments. Inevitably the possibility of nuclear accidents or leakages is highly increased causing air and soil pollution for as long as the half-life of the radioisotopes lasts. One of the most dangerous radioisotopes, because of its 30 years of half-life, is Cs\textsuperscript{137} which is widely used in some of the upper sectors as it's produced from the cleavage of U\textsuperscript{235} [1].

Therefore, instruments to measure this radiation activity in hot areas, or in consumer products, are needed [2]. There are various types of radioactivity detectors, such as Geiger–Mueller counters, silicon diodes, or compound semiconductors. But technology that seems to fit better in our requirements is a scintillation material coupled to a compact light sensitive device [3].

The Silicon Photomultiplier (SiPM) is a relatively new compact device for photon detection at very low photon rates based on arrays of avalanche photodiodes operating in the Geiger mode operation [4]. They offer good features like compactness, robustness, low cost, photon-counting capability, high quantum efficiency, high gain with a very fast response and excellent timing resolution in terms of hundreds picoseconds. In contrast to the traditional photomultiplier tubes, SiPMs are insensitive to magnetic fields and nowadays have lower cost [5]. In addition, the size of SiPM helps to build a reliable portable radiation-monitoring sensor coupled to an appropriate scintillation material in small size [6].
Cerium doped Gd$_3$Al$_2$Ga$_3$O$_{12}$ (GAGG:Ce) is a relatively new single crystal scintillator with several properties that make it interesting for several applications [7]. GAGG:Ce is non hygroscopic, and it's the brightest of the oxide scintillators with a high light yield (~46000 ph/MeV) and an emission peak at 530 nm. GAGG:Ce scintillator has a high density (6.69 g/cm$^3$), and its effective atomic number is equal to 54.4 with adequate short decay time (90ns). Furthermore, GAGG:Ce does not contain natural radioactivity, so it’s a material of choice for a personal spectrometer applications [8] [9]. In this study, a reliable and small size gamma ray detector spectrometer was developed and its feasibility was evaluated - according to the International Electrotechnical Commission (IEC) technical requirements (IEC 61526:2010) [10] - by analyzing its energy resolution, sensitivity, figure of merit, and photopercentage using a standard $^{137}$Cs source at different irradiation angles.

2. Materials and Methods.

2.1 Equipment

For our study it was used a radio source of $^{137}$Cs with low activity equal to 0.87 μCi (32.19 KBq).

The two GAGG:Ce scintillator crystals used in this study was purchased by Furukawa Co Ltd. Their dimensions are 10x10x10mm$^3$ and 10x10x20mm$^3$ with all crystal surfaces polished. The SiPM was coupled to each GAGG:Ce scintillator covered with four layers of diffusive (teflon) reflector in order to optimize the scintillation light collection. The SiPM array was purchased by SensL's and has 4x4 pixels with 3640 microcells-spads per pixel. Its total active pixel area is 13.4x13.4mm$^2$ and works properly at 29.3V bias voltage. [11]. The coupling material used between the scintillator and the entrance window of the SiPM array was BC-630 optical grease [12].

A symmetric resistive voltage division matrix was applied, which reduces the 16 outputs of the array to 4 position signals [13]. Firstly, a two-stage charge division circuit reduces the 16 output channels of SiPM at 8 by equally splitting them in a resistive matrix (4 rows-X, 4 columns-Y), and secondly into 4 position signals (Xa, Xb, Ya, Yb) by a division network of weighting resistances [14]. The digitization of the signal was achieved by a DT5720 digitizer of CAEN S.p.A. The DT5720 is a 4-channel 12-bit 250 MS/s Desktop Waveform Digitizer with 2 Vpp single ended input dynamics on MCX coaxial connectors. The DC offset is adjustable via a 16-bit DAC on each channel in the ±1V range [15].

At the end, the digitizer’s operation and the acquisition parameters’ adjustment were controlled via a laptop, with appropriate software installed. The installed software outputted 4 data files, according to the 4 input channels. A custom made software program, based on C++ code, was used in order to calculate energy resolution values of each channel extracted from full width at half maximum of photopeaks - acquired using Gaussian fit within a ±10% energy window. The final energy resolution was calculated, for each angle, by the mean of the 4 channels energy resolution values.

2.2 Experimental measurements

The radioactive $^{137}$Cs source to scintillator distance was set at 7.8cm, from the center of each crystal, and measurements repeated for 5 different angles of irradiation equal to 0°, 45°, 90°, 135° and 180° respectively. All measurements were conducted inside a light-tight box with 1 hour duration each one. In figure 1, the experimental apparatus is illustrated. According to the International Electrotechnical Commission (IEC) technical requirements for electronic $^{137}$Cs radiation dosimeters, the Maximum Rate Difference (MRD) response among different angles of irradiation should be ±20% [10]. Rate difference is the ratio of the total counts at an angle divided by the total counts in 0°, and MRD is the highest of these ratios.

Through the study of angular response, the variation in sensitivity (the recorded counts in the whole spectrum divided by emitted gamma photons of the $^{137}$Cs radio source) and the variation in energy resolution (FWHM of each photopake divided by the photopake centroid) are monitored at each exposure angle. Furthermore the two GAGG:Ce crystals are compared to observe the importance of scintillator size in detection.
Another parameter called Figure of Merit (FOM) was calculated. FOM is the Absolute Detection Efficiency (ADE%) that denotes the portion of number of gamma photons impinging in the scintillator crystal surface divided by the energy resolution (%). So FOM parameter is independent by the irradiation distance, as it contains the geometric sensitivity, and is anticipated to define the optimal design of the detector, as at least for crystal dimensions [16].

3. Results and Discussion

Figure 2 shows the rate differences among different $^{137}$Cs irradiation exposure angles for the 2 GAGG:Ce crystals. MRD response among different angles of irradiation are lower than the 20% indicating that the detector satisfies the IEC recommendation.

3.1 Angular response of Sensitivity and Energy Resolution

As presented in figure 3, the variation of the detector sensitivity response at the 5 different irradiation angles, for both crystals, is very similar. Better detector sensitivity values was achieved with the bigger GAGG:Ce crystal with dimensions equal to 10x10x20mm$^3$. Due to its higher length (20mm) it can absorb more photons even them which cross and overcome the shorter crystal distance of 10 mm (case of 0° & 180°). The detection of the ionizing radiation at energy of 662keV usually creates scattered photons due to predominante in the interactions the Compton effect, so the higher crystal mass leads to the higher possibility to detect larger number of those photons that may have a second interaction among different directions in the crystal mass [17]. In the same manner the number of totally absorbed photons via photoelectric effect and in consequence the photopercentage are higher as shown below in Table 1. The best sensitivity value is recorded at 45° because at this angle some of the gamma photons pass the crystal across to its diagonal that is larger dimension.
Figure 3: Variation of the detector sensitivity values with GAGG:Ce crystals at different angles.

On the other hand, at 135° and at 180° the sensitivity values are slightly lower mainly because of the attenuation of gamma rays from the electronic boards - especially of them with lower energy.

The energy resolution values illustrated in figure 4 does not differs importantly angle-by-angle (mean value ~9%). No significant changes are shown by changing the size of the crystal. The lower values have achieved with 10x10x10mm³ GAGG crystal equal to 8.43% (45°) and with 10x10x20mm³ GAGG crystal equal to 8.75% (0°).

3.2 Angular Response of Photopercentage and Figure of Merit

In table 1 is presented the values of the photopercentage of the 2 GAGG:Ce scintillators examined. Each photopercentage value is calculated by the number of counts recorded in the corresponding 662 keV photopeak area of the spectrum divided by the total number of counts recorded in the whole spectrum. It's about ~22% for the 10 mm thick GAGG crystal and ~26% for the longer one - with not sufficient differences in angle by angle measurement.

Figure 5 shows the FOM values for the different five angles of irradiation regarding the two different crystals examined. It is evident that the impinging crystal surface area changes respective on the exposure angle. Therefore, in the case of 90° irradiation, the area of cubic detector remains 10mm² while for the thicker crystal was 20mm². At 45° and 135° the area calculated according the Pythagorean theorem. FOM mean value for the GAGG:Ce 10x10x10mm³ was calculated equal to 4.11 lower compared with the mean value of 10x10x20mm³ calculated equal to 4.43.

Table 1. The photopercentage values

| Angles (degrees) | 10x10x10mm³ (%) | 10x10x20mm³ (%) |
|------------------|-----------------|-----------------|
| 0                | 21.71           | 25.29           |
| 45               | 22.41           | 26.07           |
| 90               | 22.69           | 27.60           |
| 135              | 21.95           | 27.91           |
| 180              | 22.09           | 24.94           |

Figure 4: Variation of the detector energy resolution values with GAGG:Ce crystals at different angles.

Figure 5: Angular response of FOM and comparison of the sizes of crystals.
This result is very encouraging in order to construct a new personal gamma spectrometer. Compared our results with previous published data that uses a SiPM based on CsI:Tl scintillator material with dimensions of 3x3x5mm$^3$ is very improved (14.7\% En. Res., ~0.0007 FOM) [16].

4. Conclusion

The GAGG:Ce based on a SiPM array personal gamma ray spectrometer has been successfully constructed, and characterized. It was find in accordance with the IEC recommendations achieving a low enough energy resolution (~9\%) with uniformity in all angles and very high detection efficiency values. According to the FOM index, which will define the optimal dimensions of the detector, the 10x10x20mm$^3$ GAGG:Ce crystal will be used in order to design an efficient compact miniature $^{137}$Cs spectrometer. The final detector dimensions could be equal of 25x25x70mm$^3$. Additional features, such as detector’s response to lower gamma energies or the construction of a new data acquisition system, in order to communicate via Wi-Fi with mobile devices, can also be implemented to improve the detector system.

Acknowledgement

“This research is implemented through IKY scholarships programme and co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the action entitled "Reinforcement of Postdoctoral Researchers", in the framework of the Operational Programme "Human Resources Development Program, Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) 2014 – 2020”.

References

[1] Kawada Y and Hino Y 1992. Nucl. Instr. and Meth. Phys. Res. A 312 11-6
[2] Yamamoto S and Ogata Y 2014. Nucl. Instr. and Meth. Phys. Res. A 753 19–23
[3] Becker E M and Farsoni A T 2014. Nucl. Instr. and Meth. Phys. Res. A 761 99-104
[4] Seitz B, Campos Rivera N, and Stewart A 2016 IEEE Trans. Nucl. Scien. 63 503-508
[5] Chen X 2014 Study of the Silicon Photomultipliers and Their Applications in Positron Emission Tomography, Hamburg
[6] Park H M, Joo K S, 2015 Nucl. Instr. and Meth. Phys. Res. A 781 1-5
[7] Yamamoto S, Kataoka J, Oshima T and Ogata Y 2016 Nucl. Instr. and Meth. Phys. Res. 821 28-33
[8] David S, Georgiou M, Fysikopoulos E, and Loudos G 2015 Phys. Med. 31 763-6
[9] David S, Valais I, Michail M and Kandarakis I 2015 J. Phys.: Conf. Ser. 637 012004
[10] International Electrotechnical Commission 2005 Radiation Protection Instrumentation, Measurement of Personal Dose Equivalent Hp(10) and Hp(0.07) for X, Gamma, Neutron and Beta Radiation: Direct Reading Personal Dose Equivalent and Monitors International Standard IEC 61526
[11] SensL, ArraySL-4 scalable silicon photomultiplier array datasheet available online at: http://www.sensl.com
[12] Park H M and Joo K S 2016 Sensors 16 919 DOI:10.3390/s16060919
[13] David S, Georgiou M, Fysikopoulos E and Loudos G 2013 Nucl. Instr. and Meth. in Phys. Res. A 702 121-5
[14] Popov V, Majewski S, Welch B 2006 Nucl. Instr. and Meth. Phys. Res. A 567 319-22
[15] Caen S.p.A., "Mod. DT5720 4 Channel 12bit - 250MS/s Digitizer, User manual (MUT)", 2014
[16] Yoo H, Joo S, Yang S and Cho G 2015 Radiat. Measur. 82 102-7
[17] Chaiphaksa W, Limkitjaroenporn P, Kim H and Kaewkhao J 2016 Prog. in Nucl. Ener. 92 48-53