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ABSTRACT

The paper discusses the problems of development of the SiPM-based gamma-detectors. The main focus is on the most effective coupling between the scintillation crystal and the SiPM. We have used a simple optical model to study the different schemes of the coupling and analyze these variants from the point of view of efficiency and uniformity of the signal on the SiPM areas. We present the process and the results of the modeling.

Keywords: Silicon Photomultipliers, scintillators, gamma-ray spectrometer, optical modeling, lightguides

1. INTRODUCTION

Scintillator-based detectors are widely used for gamma-rays, which are applied for experimental physics and for radiation monitoring, in industry, radiobiology and medicine.

Traditionally the detector device includes scintillation crystal and the photoelectronic multiplier (PM). This traditional device has excellent characteristics of sensitivity but not always appropriate for field application. In last case the unit should be strong, while the traditional photomultipliers are fragile and rather delicate to provide long life cycle. Additionally the traditional PM has relatively big size.

The novel photodetectors like silicon photomultipliers (SiPM) can help to solve both problems of big sizes for field devices and fragility, they are durable and relatively small. The device became a widely used one due to its unique properties, among them:

- High internal amplification (about 10^6), this decreases the requirements to the electronics
- Low deviations of the amplification coefficient (about 10%) and as a sequence low noise
- Low sensitivity to the temperature and voltage
- High efficiency of the visible light registration (close to the vacuum photomultipliers)
- The possibility of operation in counting photons mode and in spectrometer mode and possibility of registration of nanosecond flashes

To transfer the light of resulting scintillation to the detector a few schemes exist: optical fibers[1] or thin lightguides[2]. The simplest way is just to use the exit face of the crystal in contact to the photomultiplier entrance face, but for SiPM this variant may be not optimal. When we should detect separate scintillations, the signal is low. In this case when we place SiPM on the exit side of the scintillation crystal in contact with the exit face of the crystal it may lead to large error in signal measuring because the signal on the separate SiPM area will be strongly dependent on the scintillation location. For example, if the scintillation is close to the exit end of the crystal and we use array 2 x 2 of SiPM we can see that the signal on one of the elements of the array is much higher for that array which is closer to the scintillation location. In that case the measuring error will be rather high. So, optimal case is when we have as uniform light distribution on the SiPM as possible for all scintillation locations. To achieve it we need to choose the optical system between the crystal and the SiPM which plays a role of homogenizer for all possible flash locations.

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In the work we consider the case of using lightguides of different configuration and analyze the uniformity of signals of the SiPM array of 2 x 2. The models used are described and the results of modeling are also given.

2. DESIGN MODELS USED

The one of the methods to find an optimal way of coupling the SiPM and the crystal is to model the flash inside it initiated by thee gamma-quantum. If we do not need to consider in details the mechanism of the scintillation, we can consider only the resulting light. Thus, we can use the methods of non-imaging optics to model the light transfer to the detector surface. Additionally, we can use traditional for the illumination optics software to model the light propagation, for example Zemax[3]. In the Zemax Software for light modeling the statistical methods of ray generation are used, the similar ways and methods are commonly used for modeling the devices base on the scintillation detectors[1,4].

As the device is intended for detection of the small power radiation, it means that the device works with separate flash lights, therefore when choosing the light model we use following stipulates:

- The light may arise in any point of the scintillation crystal volume with the same probability
- Gamma-quantum leads to the luminescence of the separate small area, and from that area the radiation follows to all directions. Spectral range of the light corresponds to the spectrum of the scintillation of the given crystal (for our case it is cesium iodide CsI)
- In our case we use the crystal of cesium iodide with the sizes 14 mm x 14 mm x 28 mm. To model the material we use the optical glass with refraction index and Abbe number close to that of the CsI. This fact is important because we consider the light losses on the borders between the crystal and the air. We also consider some non-ideal transmission of the crystal.

For more convenience we use the energy of light flash (the luminous power) equal to 100 units.

To improve efficiency of the light transfer from the flash location to the detector some useful methods exist: using the additional coatings, surface polishing and grinding[5-6]. The most effective way is using the grinded surface with diffusive reflection[1,6]. In practice the crystal wrapping with special tape are commonly used, and this variant is close to the optimal one. In our design model we use the lambertian scattering applied to all surfaces of the crystal except for the one exit face.

To evaluate the signal on the SiPM we model four separate areas, with small gap between them. As the one area produces the integral signal we do not care about the number of elements on each area, we just choose them from the point of view of the calculation speed. The separate SiPM area is modeled without aperture characteristics, so we do not model the dependence of the signal from the angle of incidence to the SiPM surface, we also do not consider the blind zones between the pixels on each area.

To start trace rays we also should choose the light source model. The simplest models are[3]:

- Volume sources. Here the rays generated randomly inside the volume, the random is the character of the ray location and its direction.
- The source area (rectangular or elliptical) which emits the rays according to the law

  $$I = I_0 \cos^n \theta ,$$

  or

  $$I = I_0 \exp(-(x \cdot l^2 + y \cdot m^2)) .$$

  Here I_0 – light intensity along the axial direction, θ – the angle with respect to the axis, n – the power index. If n = 1 the source emits rays according to the Lambertian law (inside the semi-sphere), if n = 0 the source emits parallel beam of rays

  In the second equation x, y – coefficients, l, m – directional cosines in X, Y direction. If we use the second formula, we can describe the Gaussian source. But in any of these two cases the source emits in the range not greater than semi-sphere.

- Point source. Here the source is the point which can emit rays inside the cone with the angle from 0° (parallel beam of rays) up to 180° (full sphere).

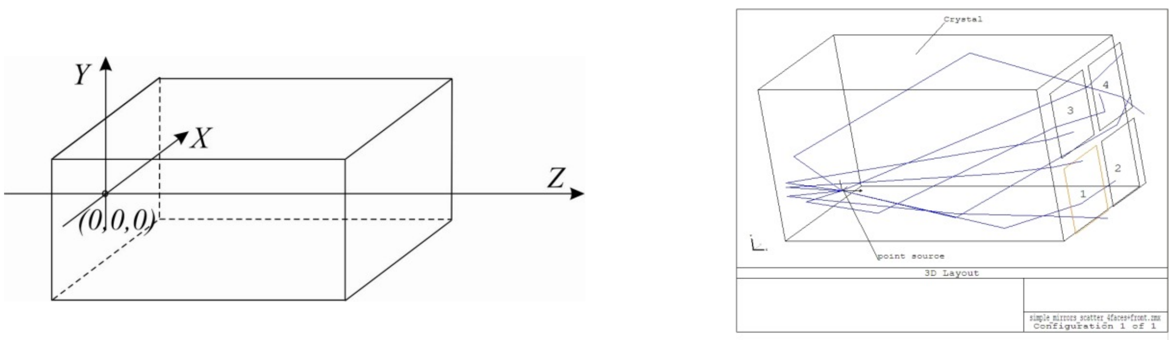
The first model can be fruitful when we need to consider the situation of high-power gamma-radiation when we have many scintillation flashes inside the volume. But this model cannot provide the information about the light location, and we cannot describe light locations inside this volume.

The second variant also can be useful when we do not care about the light propagation inside the crystal and model its exit face. Of cause, we can use it to describe the small area of the scintillation flash inside the material, but the ray generation process also will take time to provide random position of the ray and not only its direction. Additionally, in that case we can only model rays inside the semi-sphere, but the light goes in all directions from the point of scintillating.

So, the most useful variant in this case is to use point source, but in this case we neglect the size of the scintillation area. To model the signal we trace 100000 rays from the flash.

2.1 The simple model

The simplest model is the traditional way of coupling: without any additional optical system. On the figure 1a the crystal with the coordinate system is shown, on the fig.1b the model of the crystal with the four detectors is shown (we have applied reflection and lambertian scattering on all sides of the crystal except the exit one), the numbers are the numbers of the detectors surfaces (in fact the separate area of the SiPM).



a *b*

Figure 1. The simple model used for calculations: a – the coordinate system; b – the model in Zemax software

To provide results we trace 50 cases of the light source locations, each case corresponds to different coordinate along axes X, Y, Z. The coordinates were generated randomly.

On the figure 2 the results are given: for each detector there is special sign, most cases are grouped together, but there are cases with much greater signal.

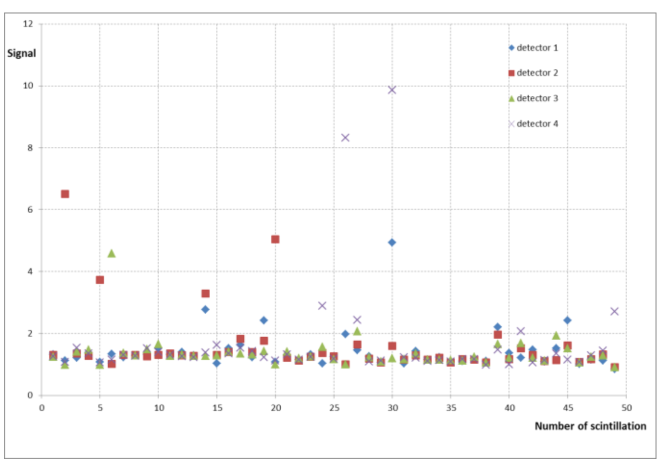


Figure 2. The results of calculation for 50 cases of light source position: signals on the four detectors.

To compare the cases and evaluate them we use standard deviation *St.dev.*:

$$St.dev. = \sqrt{\frac{\sum (x-\bar{x})^2}{n-1}} .$$

Here $\bar{x}$ - the average of the signal value, n – number of cases.

We also have used root-mean square deviation and the same value in percent:

$$rms = \sqrt{\frac{\sum (x-\bar{x})^2}{n}} \quad \text{and} \quad rms\% = \frac{rms}{\bar{x}} 100\% .$$

For the simple case without optical elements we obtain values given in the table 1.

Table 1. Calculation results for the simplest model (without coupling system)

Value	Detector 1	Detector 2	Detector 3	Detector 4
Average signal	1.426	1.554	1.36	1.663
St.dev.	0.634	1.008	0.517	1.588
RMS	0.627	0.998	0.512	1.572
RMS%	44.025	64.196	37.572	94.531

As we can see, the deviation of the signal is great because of the cases when the source (scintillation) is close to one of the detectors.

2.2 Additional optical lightguide

For improving the light uniformity in illumination optics lightguides are used, the similar lightguides are applied for light transfer in scintillation detectors and also for light concentration[7-10]. The geometry of lightguides depends on the geometry of the crystal and the detector and also is affected by the goals of the device. In our case the size of the exit face of the CsI crystal is nearly equal to the size of the detector. So, the simple variant of the lightguide together with the crystal is given on the figure 4. The lightguide is hollow, with the reflective inner surface.

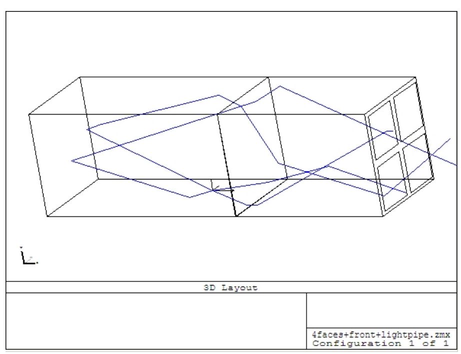


Figure 3. The system model with the simple lightguide.

The possible practical implementation of such a system is the glass parallelepiped (glass prism) with reflective coating or the hollow lightguide manufactured from the material with high reflectivity like the one used for reflectors in illumination optics.

We calculated the results both for hollow lightguide and for glass lightguide. The transmission of the glass we used (simple glass BK-7) is not ideal and the signal in this case was 15 – 20% lower compared to the hollow lightguide.

The results of calculation for the crystal with the hollow lightguide are shown on figure 5, the evaluation of the uniformity is given in the Table 2.

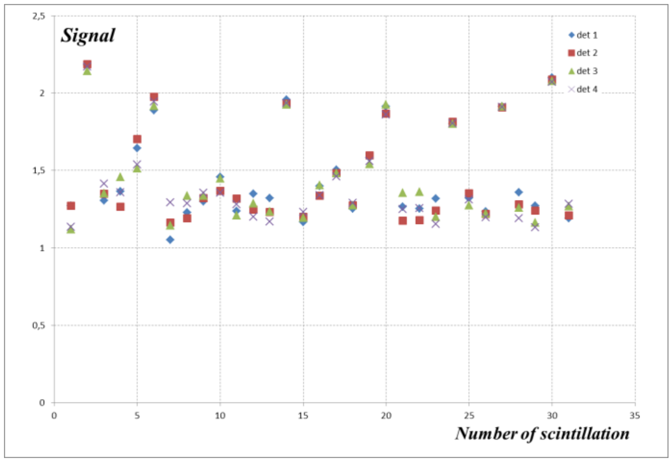


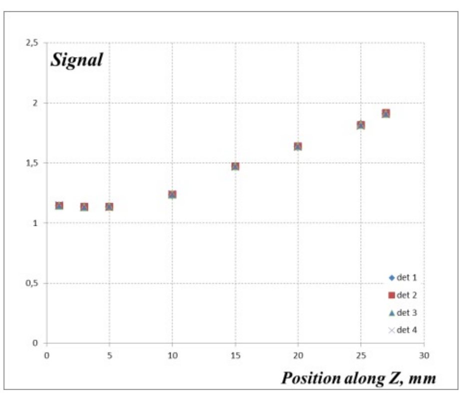
Figure 4. The results of calculation for different cases of light source position for the system with simple lightguide: signals on four detectors.

As we can see, the uniformity of the signal is much better (draw the attention to the scale of the vertical axis compared to previous case on the figure 2).

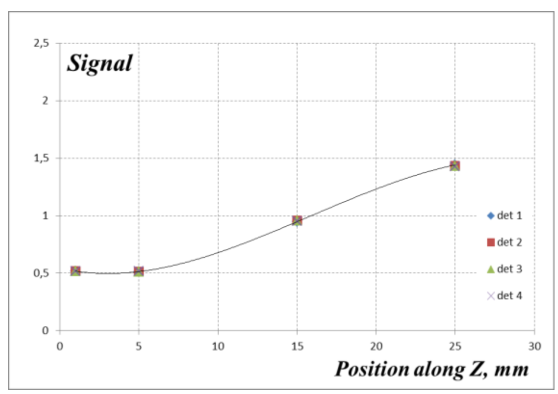
Table 2. Calculation results for the simplest coupling model

Value	Detector 1	Detector 2	Detector 3	Detector 4
Average signal	1.453	1.438	1.445	1.431
St.dev.	0.306	0.314	0.300	0.307
RMS	0.300	0.310	0.300	0.30
RMS%	20.70	21.52	20.42	21.11

The length of the lightguide was used equal to 22 mm. The more was the length of the lightguide the better was the uniformity. But for this case the length of 22 mm is close to optimum due to reflection losses which grow when the length of the lightguide is increased.



a



b

Figure 5. The results of calculation: signal dependence on the light source position along Z axis: a – for the glass with characteristics close to the crystal and transmittance 98% for 25 mm; b – for the material with transmittance 87,5% for 6 mm thickness;

The residual deviation of the signal is relatively great; unfortunately we cannot greatly affect this fact, because the reason is the absorption inside the crystal. To study that fact we calculate the signals for different light source position along the axis Z of the crystal. The results for different absorption are given on the figure 5a,b: fig.5a shows the results for the model material which has high transmission (about 98 % for visual spectrum range for the 25 mm thickness), figure 5b shows the same information, but calculated with the material with transmission 87.5% for the 6 mm thickness.

The dependence has the same character, but the signal is lower for the higher absorption. The same fact was studied by other researchers[1,10].

3. ANALYSIS AND DISCUSSION

We have considered several variants of the lightguide, some of them with characteristics of uniformity and efficiency are presented in the Table 3.

Table 3. Calculation results for the systems with different variant of coupling with the detector

System	Light losses in the design model, %	Average signal	RMS of the signal, %
Crystal wrapped, without a lightguide	14.94	1.5	60.1
Crystal with double length, wrapped, without a lightguide	16.32	0.80	88.6
Crystal, wrapped, with a shallow rectangular lightguide (length of the lightguide 22 mm)	14.08	1.44	20.93
Crystal, wrapped, with a shallow circular lightguide (length of the lightguide 22 mm)	6.25	0.81	52.32

These data show that from the point of view of signal uniformity on the SiPM in the case of nearly equal sizes of the crystal exit face and the size of the SiPM the optimum variant is the rectangular shallow lightguide. The residual non-uniformity depend on the crystal properties (light absorption inside the crystal).

Thus, for achieving the uniform signal on the SiPM lightguides of rectangular cross section may be used, the variant can be realized in practice, but the practical solution depends on many factors including the available materials and their reflectivity, transmissions of the materials and also the working conditions where the device is planned to be used. The next stage of the research will be an experimental research of the schemes.

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