Сцинтилляционный детектор GAGG:Ce с SiPM считыванием.
GAGG:Ce scintillation detector with SiPM readout.

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Here we report on our very preliminary efforts to estimate potentiality of gadolinium-aluminum-gallium garnet Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce (GAGG:Ce) with SiPM readout for conventional tasks of ionizing radiation detection. Although GAGG:Ce production technology is still under development and perfecting at FOMOS and elsewhere worldwide (some care still has to be paid to afterglow and intrinsic energy resolution), results obtained by us to date with SiPM readout are optimistic ones. In particular, energy resolution of ~12% FWHM @ 662 keV and energy noise equivalent < 30 keV were obtained at room temperature with relatively large (~2 cm$^3$) GAGG:Ce sample attached to a 6x6 mm$^2$. 
GAGG:Ce is a novel scintillation crystal having a garnet structure like well-known yttrium-aluminum garnet with well-developed growing technology, $\text{Y}_3\text{Al}_5\text{O}_{12}:\text{Ce}$ (YAG:Ce), which is used though mainly for x-ray and electron counting due to its low effective atomic number and density.

In the same time, GAGG:Ce possesses far larger effective atomic number of 51 and density 6.7 g/cm$^3$. This makes GAGG:Ce stopping power to gamma-quanta comparable or even exceeding that of CsI(Tl) or CsI(Na). Its light yield amounts to about 40,000 - 50,000 photons/MeV, which also approaches that of iodides mentioned above. Its spectral emission maximum is $\sim$530 nm, main component in scintillation decay $\sim$100 ns.
Silicon Photomultiplier (SiPM), an array of optically and electrically isolated avalanche photodiodes working in Geiger-mode, is yet another example of innovations in radiation detection techniques. Currently available with dimensions up to 6x6 mm$^2$, SiPM with its intrinsic gain comparable with that of conventional vacuum PMT is the only solid-state photo detector able to detect scintillation light at the single photon level.

SiPM technology is also under intensive development and perfecting by main players such as KETEK GmbH, SensL Corporate, HAMAMATSU, and by small independent companies as well. Some of the challenges faced by producers are increase of chip size and photon detection efficiency (PDE), decrease of optical crosstalk, dark count rate and recharging time of Geiger counters.
For our studies, we used SiPM made by SensL Corporate: MicroFC 60035 SMT. It has ~25 V breakdown voltage Vbr and spectral range from 300 nm to 800 nm. Other characteristics are listed in Table 1 below.

Table 1.

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<tr>
<td>Sensitive area, mm</td>
<td>6x6</td>
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<tr>
<td>Microcell size, mm</td>
<td>0.035x0.035</td>
</tr>
<tr>
<td>Number of microcells</td>
<td>18,980</td>
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<tr>
<td>Maximum of spectral sensitivity, nm</td>
<td>420</td>
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<tr>
<td>PDE@λ_{max}, %</td>
<td>31@Vbr+2.5V / 41@Vbr+5V</td>
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<td>Gain</td>
<td>3x10^6@Vbr+2.5V</td>
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<td>Dark current, nA</td>
<td>618-1750max@Vbr+2.5V</td>
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<td>Microcell recharge time constant, ns</td>
<td>95</td>
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MicroFC 60035 SiPM was attached to a GAGG:Ce scintillation crystal with dimensions 7x15x22 mm$^3$. Crystal was wrapped in TEFLON® reflector and attached to SiPM with 7x15 mm$^2$ side. At this preliminary stage we used read-out electronics optimized for CsI(Tl) with its 1000 ns decay time.

Figure 1 shows pulse height spectrum of Cs-137, measured with 10 cm$^3$ CsI(Tl) attached to MicroFC 60035 SMT @20°C, Vbr+3.5V. Energy resolution obtained @ 662 keV was found to be 7.9% FWHM, energy equivalent of noise – 12 keV. Absolute value of CsI(Tl) light yield used for this evaluation was found to be 50,000 photons/MeV.
Figure 1. Pulse height spectrum of Cs-137, measured with CsI(Tl) with size 15x15x50 mm$^3$ attached to MicroFC 60035 SMT.
Preliminary results obtained with GAGG:Ce are shown in Figures 2a, 2b.

Figure 2a. Pulse height spectrum of Cs-137, measured with 7x15x22 mm$^3$ GAGG:Ce crystal attached to MicroFC 60035 SiPM.
Figure 2b. Pulse height spectrum of Cs-137, measured with 7x15x22 mm$^3$ GAGG:Ce crystal. Asymmetry on the left of 662 keV peak is probably due to leakage of Gd characteristic radiation (~50 KeV) from rather thin scintillation crystal.
Energy resolution with GAGG:Ce was found to be 12.5% FWHM, energy equivalent of noise – 28 keV @20°C. This is good result for many of gamma ray detection tasks, keeping in mind i) yet non-optimal shaping time for GAGG:Ce crystal, ii) absolute value of light yield of GAGG:Ce we used is lower than that of CsI(Tl) (~40,000 photons/MeV) and iii) GAGG:Ce intrinsic resolution is still significant.

GAGG:Ce can also be used for neutron detection by gamma-radiation accompanying neutron capture. Natural mixture of gadolinium isotopes has neutron capture cross section of 49,700 Barn caused by presence of $^{157}$Gd with its neutron cross section of 259,000 barn. Total gamma quanta energy released in reaction $^{157}$Gd(n, $\gamma$)$^{158}$Gd is ~8 MeV, however only two lines from about one thousand of gamma-lines, 176 keV and 79 keV, are the most useful due to their high branching.
Conclusions.

We expect following ways of further optimization of GAGG:Ce+SiPM detector:

- Search of better geometry of crystal, providing better light collection;
- Choice of SiPM with better red light sensitivity;
- Precise choice of operating voltage for optimum balance between signal (PDE) and noise (dark current).
- Precise choice of signal shaping time constants for GAGG:Ce.

All this will be done after finalization of the crystal production technology.