Development of a high-precision color gamma-ray image sensor based on TSV-MPPC and diced scintillator arrays

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We developed a high-precision color gamma-ray image sensor with fine spatial resolution that is cost effective, widely applicable, and very sensitive, by using a diced Ce-doped $\text{Gd}_2\text{Al}_2\text{Ga}_2\text{O}_{12}$ (Ce:GAGG) scintillator array coupled with a $3.0 \times 3.0$ pixel $8 \times 8$ MPPC-array. The proposed image sensor can measure the energy of individual X-ray photons transmitted through an object. The pixel size of the Ce:GAGG scintillator array is $0.2$ mm, and the pixels are separated by $50$-μm-wide micro-grooves. The image sensor has an area of $20 \times 20$ mm$^2$ and a thickness of $1.0$ mm, and it achieves an excellent spatial resolution of $0.3$–$0.4$ mm and energy resolutions of $12\%$ and $18\%$ (FWHM) for $122$ and $59.5$ keV gamma-rays, respectively. We conducted an experiment to determine the local effective atomic number of metals using dual-energy gamma-ray sources. In addition, we developed a color-composite image using mixed images taken at three energies ($31$, $59.5$, and $88$ keV).

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1. Introduction

The demand for radiation image sensors has increased in recent years in the field of medical imaging, such as radiology, mammography, fluoroscopy, cardiology, and oncology. In addition, advanced imaging technology is widely spread in the fields of homeland security, inspection of nuclear power plants, and even in high-energy astronomy. Presently, digital radiography (DR) has become more common, and digital radiation imaging has superseded analog techniques dominated by screen-film systems.

One of the most common examples of a digital radiation image sensor is the flat-panel detector (FPD) based on active-matrix pixel arrays of either (i) photoconductors that permit the conversion of incident X-rays or (ii) scintillators that convert incident X-rays into optical photons [1]. Although the latter is indirect conversion scheme, gadolinium oxyorthosilicate $\text{Gd}_2\text{SiO}_5$ (GSO) and Ti-doped cesium iodide (CsI:TI) are most commonly used in practical commercial systems because of their cost effectiveness, ability to be fabricated over a large area, high light output, and high resolving power. In particular, the CsI:TI scintillator has received considerable attention because it can be formed in columnar or needle-like structures restricting the sideways diffusion of optical photons. For example, high-resolution, sub-100-μm gamma-ray imaging with columnar CsI:TI and electron-multiplying CCD (EMCCD) are proposed for single-emission photon tomography (SPECT) applications [2,3]. However, these columnar structures are possible only with CsI:TI, and its thickness is typically limited to less than $600$ μm. In photon-counting applications, energy resolution quickly degrades as the crystal thickness increases; thus, meaningful spectral information is not provided. Note that the CsI:TI and GOS with larger pixel sizes (typically 1 or 2 mm/pixel) are also commonly implemented as a photo-sensor in X-ray computed tomography (X-ray CT) operating in current mode, although spectral information is completely lost.

Similarly, various inorganic scintillators are proposed for medical gamma-ray imagers that provide spectral information [4]. For example, by using gadolinium oxyorthosilicate $\text{Gd}_2\text{SiO}_5$ (GSO) scintillator array of $1.9 \times 1.9 \times 7$ mm pixels coupled with position-sensitive photomultiplier tube (PSPMT), energy resolution of $15\%$ (FWHM) was achieved at $122$ keV [5]. By using a CsI:TI and NaI(Tl) scintillator array of $1.0$-mm pixels coupled with a flat panel PSPMT, a good pixel identification of $0.4$ mm is reported [6]. A Ce-doped $\text{Y}_2\text{SiO}_5$ (Ce:YSO) scintillator array of $0.8 \times 0.8 \times 7$ mm pixels coupled with a $2$-in. square PSPMT can also resolve clearly up to $1$-mm-width slit and achieve energy resolution of $20.4\%$ (FWHM) at $122$ keV [7]. A high resolution gamma-ray imager utilizing sub-mm crystal arrays up to $0.5 \times 0.5$ mm$^2$/pixel of Ce-doped ($\text{Lu}, \text{Y}_2\text{SiO}_5$):O (Ce:LYSO) and Ce-doped $\text{Gd}_2\text{Al}_2\text{Ga}_2\text{O}_{12}$ (Ce:GAGG) crystals optically coupled with...
multi-pixel photon counters were also developed and tested for small-animal positron emission tomography (PET) scanners [8,9]. However, the assembly of 0.5-mm or smaller pixel-size scintillators to a large-area matrix is technically challenging and time consuming; thus the industry is awaiting new approaches for future applications of the device.

In this paper, we propose a novel radiation image sensor with fine spatial resolution that is cost effective, widely applicable, and highly sensitive. Moreover, it performs photon counting. In our approach, we fabricated a fine-pitch Ce:GAGG scintillator array by using a dicing saw and employing a large-area 8 \times 8 multi-pixel photon-counter (MPPC) array for readout. This paper reports the evaluation of the performance of the new image sensor using gamma rays. We also conducted an experiment to determine the local effective atomic number of metals using dual energy. Finally, we produced a color-composite image using compositing images taken at three energies (31, 59.5, and 88 keV) for a brief performance demonstration of the device.

### 2. High-precision, MPPC-based scintillator array

#### 2.1. Fine-pitch Ce:GAGG scintillator array

The size of the fine-pitch Ce:GAGG scintillator array was 20 \times 20 \times 1 \text{ mm}^3, and the size of each pixel was 0.2 mm. A glass substrate having the same size as the scintillator array was attached to the array. A photo of the fine-pitch Ce:GAGG scintillator array is shown in Fig. 1. Ce:GAGG has the excellent features of high light yield, high density, fast decay time, and no internal radiation or hygroscopicity. Table 1 summarizes the basic characteristics of Ce:GAGG and other scintillators [10,11]. All the surfaces of the Ce:GAGG pixels were mechanically polished.

#### Table 1

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Ce:GAGG</th>
<th>Ce:LYSO</th>
<th>GOS</th>
<th>CsI:Tl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>6.63</td>
<td>7.30</td>
<td>7.28</td>
<td>4.51</td>
</tr>
<tr>
<td>Light yield (photon/MeV)</td>
<td>46,000</td>
<td>30,000</td>
<td>66,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>88 (91%), 258 (9%)</td>
<td>40</td>
<td>3000</td>
<td>1000</td>
</tr>
<tr>
<td>Peak wavelength (nm)</td>
<td>520</td>
<td>420</td>
<td>512</td>
<td>565,420</td>
</tr>
<tr>
<td>Internal radiation</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Slight</td>
</tr>
</tbody>
</table>

Fig. 1. Photo of fine-pitch Ce:GAGG scintillator array.

Fig. 2. Photo of 8 \times 8 MPPC (TSV) array.

Fig. 3. Photo of slit phantoms used to measure spatial resolution.
2.2. $8 \times 8$ MPPC (TSV) array

MPPCs are a type of silicon photomultiplier (SiPM) with high gain ($10^5$ to $10^6$), low bias supply ($\pm 100 \text{ V}$), fast timing characteristics ($\approx 50$ to $100 \text{ ns}$ decay), and insensitivity to magnetic fields [9]. They are easy and inexpensive to scale up in size.

We used an MPPC with the following features: the number of channels was $8 \times 8$ (64 channels), the effective photosensitive area size was $3.0 \times 3.0 \text{ mm}$ per pixel, and the avalanche photodiode (APD) pitch was $50 \text{ mm}$. Using through-silicon via technology (TSV) instead of wire-bonding eliminates the need for a wire-bonding pad. Consequently, TSV allows a larger active area and less dead space, yielding high photon-detection efficiency (PDE) [12]. The MPPC's gain was $1.25 \times 10^6$, and its supplied voltage was $66.50 \text{ V}$. A photo of the $8 \times 8$ MPPC (TSV) array (Hamamatsu Photonics: S12642-0808-3553(X)) is shown in Fig. 2.

2.3. Slit phantoms

To evaluate the spatial resolution, we used three slit phantoms. For slit phantom 1, the slit widths were 1.2, 1.0, 0.8, and 0.6 mm. For slit phantom 2, the slit widths were 0.6, 0.5, 0.4, and 0.3 mm. Slit phantom 3 had 1.1-mm slit widths and 4-mm separations. These phantoms were made of 2-mm-thick tungsten and are shown in Fig. 3.

2.4. Experimental setup

The fine-pitch Ce:GAGG scintillator array with a glass substrate was optically coupled to the $8 \times 8$ MPPC (TSV) array with silicon optical grease (OKEN 6262A). The detector was covered with polytetrafluoroethylene tape as a reflector. The radioactive source was positioned 4.0 cm above the surface of the fine-pitch Ce:GAGG scintillator array. The experimental setup is shown in Fig. 4.

To reduce the number of output signals from the MPPC array, we used a charge-division readout technique. Using the two-dimensional (2D) resistive charge-division network shown in Fig. 5, we compiled the 64 signal outputs from the MPPC array into four position-encoded analog signals. The capacitance of the coupling condenser was 0.1 μF. The 2D resistive charge-division network was attached to the reverse side of the MPPC.

The four position-encoded analog signals were amplified by a factor of 10 using a wideband amplifier (Phillips Scientific Model 6954) and sent to a linear fan I/O module (Phillips Scientific Model 740), which generated the sum of the signals as well as four individual signals. The sum of the signals was fed into a discriminator (Technoland N-TM 405), which generated a trigger signal. The trigger signal was sent to a gate-and-delay generator (Technoland N-TM 307) to activate a gate signal 800 ns wide. Subsequently, the gate signal was fed into a charge-sensitive analog-to-digital converter (ADC) (HOSHIN VO05). The four individual signals were delayed using a 100-ns delay circuit (Technoland N-TS 100) and attenuated (22 dB) by an attenuator (Technoland N-TM 224a). Finally, each signal was sent into the charge-sensitive ADC to convert the analog signals into digital signals. The light-emitting position was digitally calculated using Eqs. (1) and (2) where $P_i$ ($i = 0$–3) are the output digital values of the charge-sensitive ADC shown in Fig. 5. A diagram of the data-acquisition process is shown in Fig. 6:

\[ X = \frac{P_2 + P_3 - P_0 - P_1}{P_0 + P_1 + P_2 + P_3} \]  
\[ Y = \frac{P_0 + P_2 - P_1 - P_3}{P_0 + P_1 + P_2 + P_3} \]

2.5. Performance testing

All the experiments were conducted at 20 °C with a bias voltage of 66.50 V.

First, we acquired a 2D position histogram of the fine-pitch Ce:GAGG scintillator array using a $^{60}$Co point source, as shown in Fig. 7(a). Despite the very small pixel size of 0.20 mm, most pixels were clearly resolved. An enlarged view of the 2D position histogram is shown in Fig. 7(b). After the acquisition of the 2D position histogram, we conducted peak searching and defined a pixel region.

Then, we measured the energy spectrum of $^{241}$Am and $^{57}$Co. Energy calibration was performed pixel-by-pixel. Subsequently, we generated the sum spectra for all pixels and calculated the...
energy resolution at 59.5 and 122 keV. The energy spectra for $^{57}$Co and $^{241}$Am are shown in Fig. 8. The energy resolution was 18.6% FWHM at 59.5 keV and 12.5% FWHM at 122 keV.

Finally, we measured the spatial resolution at 59.5 and 122 keV using the slit phantoms (Fig. 3). A slit phantom was positioned on the surface of the fine-pitch Ce:GAGG scintillator and irradiated by $^{241}$Am and $^{57}$Co. An image was obtained using photo-absorption events at 59.5 or 122 keV for each pixel. Then, the image was compensated by a sensitivity map defined by dividing the number of photo-absorption events in each pixel by the maximum number of photo-absorption events. Images of the slit phantoms measured at 59.5 and 122 keV are shown on the right and left sides, respectively, of Fig. 9. For phantom 1, all slits were resolved clearly at both 59.5 and 122 keV. For phantom 2, the slit 0.3 mm wide was not resolved at 59.5 keV; however, it was resolved for 122 keV. Note that these spatial resolutions are limited by the pixel size of the MPPC array rather than that of the GAGG scintillator array. Therefore, we expect to improve the spatial resolution by using a 1.0 × 1.0-mm$^2$ pixel MPPC array, according to previous research [13].

3. Challenge to multi-color imaging

3.1. Basic concept

We determined the local effective atomic number of metals by using the difference in transmittance between low and high energy. With high energy, the number of detected photo-absorption events without metal, $I_{0\text{High}}$, and the number of detected photo absorption events with metal (thickness is $d$, density is $\rho$), $I_{\text{High}}$, are related by

$$I_{0\text{High}} = I_{\text{High}} e^{-\mu_m E_{\text{High}}/\rho d}$$

where $\mu_m(E_{\text{High}})$ is the mass-attenuation coefficient of the metal at the energy $E_{\text{High}}$. Similarly, $I_{0\text{Low}}$ and $I_{\text{Low}}$ are associated by

$$I_{0\text{Low}} = I_{\text{Low}} e^{-\mu_m E_{\text{Low}}/\rho d}$$
According to Eqs. (3) and (4), the ratio (defined as the k-factor) of the mass-attenuation coefficient of metal between two different energies is calculated:

\[
k = \frac{\mu_m(E_{\text{low}})}{\mu_m(E_{\text{high}})} = \frac{\ln(k_{\text{low}}/k_{\text{low}})}{\ln(k_{\text{high}}/k_{\text{high}})}
\]

(5)

The k-factor is a function of the effective atomic number \(Z\), and we can calculate it for all natural elements. The calculated k-factor as a function of \(Z\) is shown in Fig. 10.

We approximately fitted the k-factor with respect to the atomic number \(Z\) using the following equation for three different intervals: \(Z \in 1-10; Z \in 11-40; \) and \(Z \in 41-52 [14]\):

\[
k(Z) = \frac{p_1 + q_1Z + r_1Z^2}{p_2 + q_2Z + r_2Z^2}
\]

(6)

Thus, we determined the dependency of the k-factor as a function of the atomic number \(Z\).
3.2. Experimental setup

In this experiment, we used two different energies: $E_{\text{low}} = 59.5$ keV and $E_{\text{high}} = 122$ keV. To determine the local effective atomic number for metals, we first measured the number of detected photo-absorption events without metal at 59.5 and 122 keV. Next, we positioned four metals: high-purity 2-mm-thick titanium; 1-mm-thick iron; 1-mm-thick copper; and 1-mm-thick brass, which is a blend of 60% copper and 40% zinc, on the detector (Fig. 11) and measured the number of detected photo-absorption events. We then calculated the $k$-factor using Eq. (5). Finally, we calculated the atomic number using the dependency of the $k$-factor as a function of the atomic number $Z$, according to Eq. (6).

3.3. Material identification

Table 2 presents the experimental atomic number of metals $Z_{\text{ex}}$ and theoretical effective atomic number $Z_{\text{ef}}$. The error is calculated using the formula of propagation of errors. We determined the atomic number for each metal with a very high precision. A slight offset between $Z_{\text{ex}}$ and $Z_{\text{ef}}$ was ascribed to effects caused by scattering events, which for simplicity are not considered here. The purity of each metal is also important for this determination.

3.4. Three-color imaging

Our novel image sensor can measure the energy of individual X-ray photons transmitted through an object. It can obtain an image at each X-ray energy; thus, conventional monochromatic X-ray images are changed into color X-ray images.

First, we attempted to obtain color images using gamma rays. The object shown in Fig. 12 was positioned on the detector. We obtained images at 31 keV of $^{133}$Ba, 59.5 keV of $^{241}$Am, and 88 keV of $^{109}$Cd. After obtaining images at each energy level, we combined the images to obtain a color-composite image.

The images taken at 31 keV of $^{133}$Ba, 59.5 keV of $^{241}$Am, and 88 keV of $^{109}$Cd are shown in Fig. 13, and the composite image is shown in Fig. 14. The color-composite image enables us to distinguish between heavy and light materials clearly, compared with the monochromatic images.

3.5. Application for the future

In the previous sections, we showed that a diced Ce:GAGG scintillator optically coupled with a large-area MPPC-array provides excellent performance both for high-precision gamma-ray imaging and spectroscopy measurements. Although the detector itself is still small (20 × 20 mm$^2$) and leaves much room for improvement, this simple imager seems to surpass the conventional FPD in some applications. First, blade dicing is a very common technique that is applicable to any scintillator material, not limited to Ce:GAGG. We are currently fabricating thicker diced scintillator arrays of various scintillators that will be reported in the forthcoming paper. Second, dicing is much easier and more cost effective than assembling individual-pixel scintillators or a columnar structure of CsI:Tl. Moreover, we obtain an energy resolution of 12% and 18% (FWHM), respectively, for 122 keV and 59.5 keV gamma-rays, as well as 0.3–0.4 mm spatial resolution with 1-mm-thick Ce:GAGG, which is difficult to achieve either by conventional FPDs or photon-counting EMCCD systems [2].

Owing to the high amplification gain of MPPC, signal processing is also very simple, such that only four output signals through a resistive charge-division network is used to determine the position of the incident gamma rays. Ultimately, we hope to use similar diced scintillators and MPPCs in a next-generation CT scanner, namely the photon-counting CT. To realize a photon-counting CT, however, the detector must respond to a very high rate, typically $10^5$ counts/s/mm$^2$. Not only the MPPC but also the decay time of the scintillator is a critical factor for the optimization. We are starting to examine scintillator-MPPC based photon-counting CT systems using Pr-doped

| Table 2: Result of determination of local effective atomic number of metals. |
|-----------------|---|---|
| Metal           | $Z_{\text{ex}}$ | $Z_{\text{ef}}$ |
| (1) Brass       | 30.0 ± 0.1 | 29.4 |
| (2) Iron (Fe)   | 25.7 ± 0.1 | 26.0 |
| (3) Titanium (Ti)| 20.8 ± 0.1 | 22.0 |
| (4) Copper (Cu) | 29.6 ± 0.1 | 29.0 |

Fig. 10. $k$-factor with respect to atomic number for all natural elements, with $Z$ ranging from 1 to 52.

Fig. 11. Four metals to determine atomic number.

Fig. 12. Object for obtaining color-composite image.

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Lu$_3$Al$_5$O$_{12}$ (Pr:LuAG) or Ce-doped YAlO$_3$ (Ce:YAP) scintillators; the first results for these will be reported in the near future.

4. Conclusion

This paper reports the development of a novel gamma-ray image sensor using a Ce:GAGG scintillator array coupled with a $8 \times 8$ MPPC array. It is cost effective, highly versatile, and very sensitive, and the dicing technique can be applied for all scintillators having a thickness within 2 mm. We achieved excellent spatial resolution of 0.3–0.4 mm and an energy resolution of 12.5% (FWHM) at 122 keV. We demonstrated that it is possible to determine the local effective atomic number with high precision owing to the photon-counting technique. Moreover, three-color composite images enabled us to distinguish between heavy and light materials clearly compared with monochromatic images.

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