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Recent progress of MPPC-based scintillation detectors in high precision X-ray and gamma-ray imaging

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ABSTRACT

The multi-pixel photon counter (MPPC) is a promising light sensor for various applications, not only in physics experiments but also in nuclear medicine, industry, and even high-energy astrophysics. In this paper, we present the current status and most recent progress of the MPPC-based scintillation detectors, such as (1) a high-precision X-ray and gamma-ray spectral image sensor, (2) next-generation PET detectors with MRI, TOF, and DOI measurement capabilities, and (3) a compact gamma camera for environmental radiation surveys. We first present a new method of fabricating a Ce:GAGG scintillator plate (1 or 2 mm thick) with ultra-fine resolution (0.2 mm/pixel), cut using a dicing saw to create 50 μm wide micro-grooves. When the plate is optically coupled with a large-area MPPC array, excellent spatial resolution of 0.48 mm (FWHM) and energy resolution of 14% (FWHM) are obtained for 122 keV gamma rays. Hence, the detector can act as a convenient "multi-color" imaging device that can potentially be used for future SPECT and photon-counting CT. We then show a prototype system for a high-resolution MPPC-based PET scanner that can realize $\simeq 1$ mm (FWHM) spatial resolution, even under a strong magnetic field of 4.7 T. We develop a front-end ASIC intended for future TOF-PET scanner with a 16-channel readout that achieves a coincidence time resolution of 489 ps (FWHM). A novel design for a module with DOI-measurement capability for gamma rays is also presented by measuring the pulse height ratio of double-sided MPPCs coupled at both ends of scintillation crystal block. Finally, we present the concept of a two-plane Compton camera consisting of Ce:GAGG scintillator arrays coupled with thin MPPC arrays. As a result of the thin and compact features of the MPPC device, the camera not only achieves a small size ($14 \times 14 \times 15$ cm^3) and light weight (1.9 kg) but also excellent sensitivity, compared to the conventional PMT-based pinhole camera used in Fukushima. Finally, we briefly describe a new product recently developed in conjunction with Hamamatsu Photonics K.K. that offers improved sensitivity and angular resolution of $\Delta\theta \sim 8^\circ$ (FWHM) at 662 keV, by incorporating DOI-segmented scintillator arrays.

1. Introduction

The multi-pixel photon counter (MPPC), also referred to as a silicon photomultiplier (Si-PM), was developed by Hamamatsu Photonics K.K. (hereafter, Hamamatsu) and is a solid-state photon counting device consisting of hundreds to over ten thousand avalanche photodiode (APD) pixels in the Geiger-mode. Ref. [1] gives details of the design concept, operating mode and basic performance of MPPCs. As shown in Fig. 1, the MPPC has many advantages which are similar to those of conventional linear-mode APDs (e.g. [2,3]), such as insensitivity to magnetic fields, robustness and compactness, and high signal amplification gain up to the million level (making it comparable to photo-multiplier [PMT] gain). However, the dynamic range of the MPPC is often limited by the number of Geiger-mode APD pixels comprised in the device, resulting in a non-linear response to the number of incident photons. Moreover, thermal electrons often trigger a Geiger discharge, thereby making the substantial contamination of dark counts a possible problem, especially for weak photon detection. The technical optimization of the MPPC device is still underway, but the latest products successfully achieve a substantial reduction of dark counts and improved photon detection efficiency, in

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addition to pixel size miniaturization to extend the device's dynamic range [4].

Hamamatsu has released a variety of MPPC products since 2008. Particularly noteworthy are position-sensitive arrays (e.g., 2×2 or 4×4 matrices of MPPC pixels) that may replace conventional multi-anode PMTs in certain applications. The first MPPC array (released in 2010) was an assembly of discrete 3×3 mm^2 pixels (see, Fig. 1). Then, in 2012, a large-area, monolithic MPPC array fabricated in 3-side buttable packages was released. This MPPC array has already been tested for various applications [5–7] and is a key device that will be demonstrated in later sections of this paper. Finally, through-silicon via (TSV) technology enables the production of a large active area and less dead space in 4-side buttable package of the MPPC-array and, in 2014, Hamamatsu took on the challenge of fabricating various types of TSV-MPPCs, arranged into 8×8 or 16×16 channels (ch) [8].

	PMT	PD	APD	MPPC
Gain	$10^{5\text{-}6}$	1	50-100	$10^{5\text{-}6}$
Q.E (PDE)	>25	> 80		>25
Volume	large			small
B tolerance	No			Yes
Structure	complex			simple
Elec Power	high			low

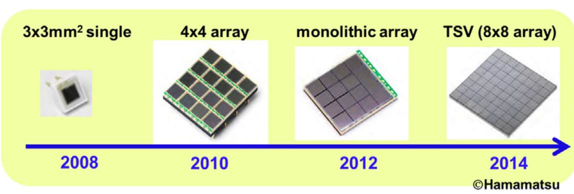

Fig. 1. (*Upper*) Basic properties and advantages of MPPC in comparison with conventional PMTs, PDs and APDs. (*Bottom*) A brief history of MPPC development and related products developed with Hamamatsu Photonics K.K.

Given the current development status, various MPPC applications are now being proposed, not only in physics experiments but also in nuclear medicine, industry, and even high-energy astrophysics. In this paper, we focus on reviewing the current status and most recent progress of MPPC-based scintillation detectors by considering applications such as a high-precision X-ray and gamma-ray spectral image sensor (in Section 2), next-generation PET detectors having magnetic-resonance imaging (MRI), time-of-flight (TOF) , and depth-of-interaction (DOI) measurement capabilities (in Section 3), and a compact gamma camera for environmental radiation surveys (in Section 4).

2. Multi-color, ultra-fine resolution scintillation camera

X-ray and gamma-ray imaging techniques using fine scintillator arrays coupled with optical sensors are commonly used in medicine, physics experiments, and homeland security. For example, gamma-cameras based on PMTs have a long history, depending on the scintillator used and detector arrangement. In some cases, spatial resolutions at the sub-millimeter level has been recorded (e.g., [12,13]), but this is still far from the 0.1 to 0.2 mm resolution possible with flat panel X-ray detectors (FPD; e.g. [9]). However, FPDs are minimally sensitive to gamma rays, high in cost, and unsuitable for photon counting or measuring spectra. Traditional PMTs coupled with

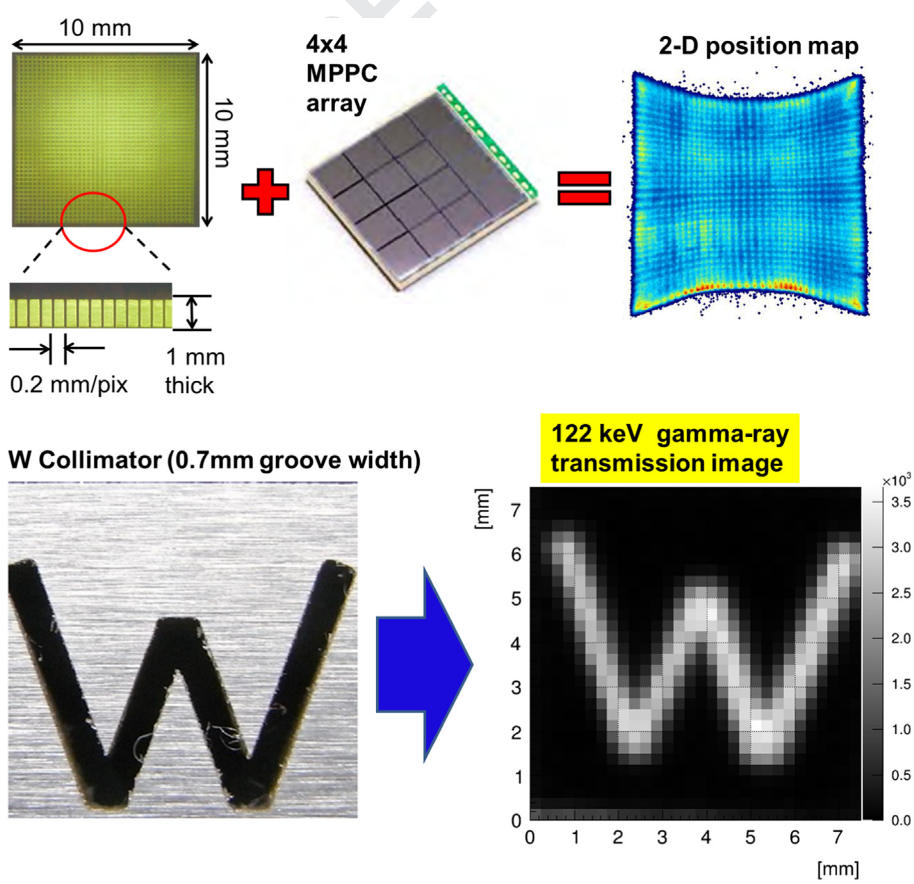

Fig. 2. (*Top*) Photo of diced Ce:GAGG scintillator array to be coupled with MPPC array, with a flood map taken with a ^{60}Co source shown on the right. (*Bottom*) Tungsten collimator (with a 0.7 mm-wide W-shaped groove) and resultant image, taken at 122 keV.

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