Compact LaBr$_3$: Ce Gamma Ray Detector with Si-APD Readout

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Abstract. Brillance 380™ (LaBr$_3$:Ce) crystal scintillators available from Saint-Gobain Crystals have achieved 2.6% FWHM for 662keV photons $^1$. This is accomplished with PMT light sensors. Attempts to have similarly good results with PIN photo-diodes and APDs have not been successful. PIN photodiodes do not have any gain and the signal to noise ratio is poor at room temperature. Similarly, even though APDs have sufficient gain, they have poor signal to noise at room temperature. Recently there have been improvements in APDs decreasing the internal noise and increasing their sensitivity, making them an excellent light sensor. With the improved APD, it is now possible to achieve performance with a solid state light sensor comparable to that of PMTs. We have measured 2.8% for 662keV gamma rays at room temperature using an APD for a light sensor on a 20mm long crystal of 1.6cc volume. APDs have advantages of compactness, inherent ruggedness and minimal sensitivity to magnetic fields. Such a device is very practical for hand held and portable field measurement applications$^1$.

$^1$Performance reported in SGC literature.

Keywords: avalanche photodiode, energy resolution, scintillator, LaBr$_3$: Ce, gamma detection.


1. INTRODUCTION

Cerium-doped lanthanum bromide is a premium scintillator with properties that make it the material of choice for some applications in security, medical imaging, and geophysics $^{1,2}$. In particular, it has very high scintillation light yield ($\sim$65,000 photons/MeV), fast emission (decay time of 16 ns), good density (5.1 g/cc), and the best energy resolution at room temperature among commercially available scintillators (≤ 3% FWHM at 662 keV).

Most scintillation detectors use photomultiplier tubes (PMT) because they provide a very high internal gain and an excellent signal to noise ratio. But the gain variability, the large size and the fragility can make PMTs undesirable in some applications.

For instance, the gain drift due to the magnetic field presents serious problems in nuclear accelerators application, near the bending and focusing magnets of the spectrographs. In other applications closely packed detectors are preferred as in imaging arrays. The size and poor tolerances of glass envelope PMTs are not suitable whereas Photo-diode (PD) arrays are thin devices with tight tolerances. Thus, a complete detector can be made that is only slightly larger than the crystal itself, even including a preamplifier.

Some other drawbacks of PMTs are: high operating voltage, power consumption of the voltage divider (VD), weight of the PMT and VD, low quantum efficiency, the fragility of the glass bulb, and the radiation hardness. The solid state photo-detectors do not have these disadvantages. Some may require a few hundreds of Volts, but with minimal power consumption. They feature high quantum efficiency, and are insensitive to magnetic fields. Their main limitation is size: the largest PIN photodiodes available are about 28mm and the largest APD is about 18mm.

So far, silicon PIN photodiodes are used with CsI(Tl) scintillation detectors. The quantum efficiency is well matched to the emission wavelength of this crystal, but the absence of internal gain is a serious drawback. The electronic noise impairs low energy measurements. A typical low energy threshold of 50keV and a pulse height resolution (PHR) of 5.5% at 662keV are achievable at room temperature.

There are other promising optical devices: Fiorini $^3$ has reported a resolution of 2.7% at 662 keV with
a Silicon Drift Diode (SDD). Developments with silicon photo-multipliers (SiPM) “4” are encouraging. Hybrid PMTs (HPMT) also show excellent potential “5”.

As regards avalanche photodiodes (APDs), the improvement in the noise level, the sensitive area and the quantum efficiency allow now excellent PHR “6 7 8”. More specifically, Moszynski has reported 4.8% at 662keV on a CsI(Tl) crystal “9”. Shah has reported a PHR of 2.4% at 662keV on LaBr₃:Ce with a cooled APD “10”.

The purpose of this paper is to describe new results obtained with LaBr₃: Ce scintillator using an APD from Hamamatsu. The performance achieved is comparable to that obtained with good PMTs.

2. RESULTS

The measurements reported here were obtained with a silicon APD model S8664-1010 coupled to several different crystals of lanthanum bromide doped with cerium (LaBr₃:Ce), sold by Saint-Gobain under the trade name BrilLanCe™ 380. The performance was measured at 662keV and pulse height (PH) and pulse height resolution (PHR) values are reported. Measurements were also taken on the low energy noise threshold and for system linearity up to 5.6 MeV. We report more specifically on a compact probe that exhibits a resolution of 2.8% at 662keV and has a low energy noise level of 8 keV. This detector weights 60g and has an overall package volume of 3x3x5.5cm³ (Fig. 1). It includes a 9x9x20mm³ BrilLanCe™ 380 scintillator, a 10x10mm² APD and a preamplifier. The best performance is achieved when the electronic components are encapsulated with the scintillator providing an integral package that is compact, rugged and shielded against electromagnetic radiation.

As shown in Table 1, the performance of parallelepiped crystals coupled to an APD strongly depends on the matching between the cross sectional area of the crystal surface to be coupled and the sensitive area of the APD. If the cross section of the crystal is bigger than the cross section of the APD, the resolution will be poorer because of incomplete light collection. Small crystals like the φ6xh6 (dimensions in mm) have good light collection, but can be difficult to manufacture in small quantities. The optimum cross section of a parallelepiped crystal has a surface just slightly smaller than the APD’s. Therefore the surface area of the scintillator was selected to match the area of the sensitive surface of the APD.

The detector design is intended to be compact, minimizing the distance between optical and electronic components. The components are in a hermetically sealed housing 0.5mm thick that passes x-rays and gamma-rays. The LaBr₃:Ce crystal is optically bonded directly to the APD and the pins of the APD are soldered directly to the preamplifier circuit board. With these optimisations a low noise threshold and excellent pulse height resolution are possible as seen in Figs. 2 and 3.
FIGURE 2. An Am241 spectrum obtained with the probe shown in Fig. 1.

FIGURE 3. The spectrum of a Cs137 source measured by the detector shown in Fig. 1. The PHR of the photopeak is 2.8% and the noise edge is 8keV.

The excellent energy resolution of LaBr3:Ce is attributed to the linearity of its response - the light output is very nearly proportional to the photon energy. This property is maintained with the APD. In Fig. 4 the measured output vs. photon energy up to 5619keV is plotted. The photons are the Ba x-rays (36keV), the gamma-rays from the Th$^{232}$ decay chain (239 keV, 583 keV, 911 keV, 1593 keV, 2615keV), from O$^{16}$ (6130keV first and 2nd escape peaks) and 511keV. The O$^{16}$ first excited state emission is produced with a Cm$^{244}$/C$^{13}$ source. This small detector has poor efficiency for the full energy peak at 6130keV so the 1st and 2nd escape peak are used. The lines are linear least squares fits to the data. The linearity is quite excellent throughout the energy range. The results are shown for three different bias settings.

FIGURE 4. Linear least squares fits from 36keV (Ba x-rays) to 5619keV (O16 single escape peak) for 3 bias settings are shown. The linearity of response is excellent.

Reverse positive bias was applied to the cathode of the APD through a 470Mohm load resistor as shown in Fig. 5. The preamplifier signal is taken directly from the cathode. This circuit was used throughout for all measurements. The gain as a function of bias for the 662keV Cs137 gamma ray is shown in Fig. 6. As the bias increases 250V, the gain increases non-proportionally 100X.

FIGURE 5. The circuit showing the application of reverse positive bias to the APD cathode and the preamplifier connection.
FIGURE 6. The gain is not proportional to the bias. It increases 100x for a bias change from 250V to 500V.

The bias setting also affects the signal to noise response. As the bias rises, the capacitance reduces but the leakage current increases. Both the capacitance and the leakage current can degrade the signal by contributing to noise of the detector. To find the bias voltage that optimizes the resolution the PHR and noise threshold as a function of bias was measured. For this APD, the noise and PHR are both at a minimum at 425V bias. These data are show in Fig. 7.

FIGURE 7. The PHR and the noise threshold measured at 662 keV Cs137 versus bias setting. The best performance occurs at a bias of 425V.

The shaping time of the main amplifier is also an important setting. The longer the shaping time, the more noise is integrated and the worse the PHR. Fig. 8 shows that the noise edge decreases with shaping time. The PHR also follows this trend but then it plateaus or increases below 0.5 microseconds. The best PHR is obtained for a shaping time of 0.5 microseconds. The noise threshold is slightly lower with a 0.25 microseconds shaping time at 7keV but the PHR is slightly worse.

FIGURE 8. The noise threshold and the PHR as a function of the shaping time of the main amplifier for 662keV gamma rays. The noise threshold decreases with shaping time but the PHR has a minimum.

It should be noted that the previous settings may vary unit to unit as there is a spread in the APD properties due to variability in the production process, especially as regards to gain and breakdown voltage “11”. The optimum bias setting should be determined individually for each APD.

The gain of the avalanche process depends on temperature. The completed detector assembly was placed in a thermal chamber and the PH and PHR were measured as a function of temperature. The temperature ramp was 5ºC/hr and spectra were taken for 10 minute intervals. Thus, each spectrum includes a 5/6ºC temperature change during the measurement interval. Fig. 9 shows the results at a bias setting of 375V. The slope of the curve near 25ºC is 4%/ºC.

FIGURE 9. The PH and PHR as a function of temperature. The crosses are the PHR with the scale to the left and the Xs are the relative PH with the scale to the right. The PH is normalized to one at 25ºC. The slope of the curve near 25ºC is 4%/ºC.
6%/°C. Note the dip in the PHR at 25°C. There was a two hour soak at that temperature and the data taken during that time period does not include a PH change with temperature. The PHR drops from 3.4% to 3.0%.

3. CONCLUSION

The data presented here verifies that it is possible to build a small compact probe using a LaBr₃:Ce scintillator with performance as good as what can be achieved with a PMT. Specifically, a 0.9x0.9x2cc LaBr₃:Ce scintillation crystal coupled to an S8664-1010 APD was measured to have excellent linearity up to 6MeV and energy resolution of 2.8% for 662keV gamma rays. The only caveat is that the response of the APD changes significantly with temperature. It is necessary to keep the system at constant temperature during the measurement interval.

REFERENCES


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