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GAMMA RAY SPECTROSCOPY AND TIMING USING LSO AND PIN PHOTODIODES*

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Abstract

The high density, high light output, and short decay time of LSO (lutetium orthosilicate, Lu_2SiO_5:Ce) make it an attractive scintillator for gamma ray spectroscopy. The low cost, small size, high quantum efficiency, and ruggedness of silicon photodiodes make them attractive photodetectors for this same application, although their high noise (compared to a photomultiplier tube) reduces their appeal. In this work we measure the gamma ray energy resolution, timing accuracy, and conversion factor from gamma energy to number of electron-hole pairs produced with a 3x3x22 mm^3 LSO scintillator crystal read out with a 3x3 mm^2 silicon PIN photodiode. When the detector is excited with 511 keV photons, a photopeak centered at 1940 e^- with 149 keV fwhm is observed and a timing signal with 35 ns fwhm jitter is produced. When the detector is excited with 1275 keV photons, a photopeak centered at 4910 e^- with 149 keV fwhm is observed and a timing signal with 25 ns fwhm jitter is produced. While these performance measures are inferior to those obtained with photomultiplier tubes, they are acceptable for some applications.

1. INTRODUCTION

The goal of this work is to evaluate the gamma ray measurement properties of small cerium doped lutetium orthosilicate (Lu_2SiO_5:Ce, commonly known as LSO) scintillator crystals read out with a silicon PIN photodiode. This study is motivated by the need for several applications (notably positron emission tomography or PET) to identify gamma rays with good spatial, timing, and energy resolution.

While photomultiplier tubes are capable of converting optical signals into electrical pulses with outstanding gain bandwidth product and low noise, they have several drawbacks that limit their usefulness in some applications. Their gain is temperature dependent and drifts with time, they require kilovolt power supplies, are sensitive to magnetic fields above a few gauss, have relatively low (typically 20%) quantum efficiency, are relatively large (minimum dimension of the optical surface is approximately 1 cm, minimum depth is approximately 8 cm), and are relatively expensive (typically several hundred dollars). The size constraint makes it difficult to read out close packed arrays of small scintillator crystals, such as those found in medical imaging, astrophysics, and particle physics, even with multi-anode or position sensitive photomultiplier tubes, as these devices have a large non-photosensitive area at the perimeter, significant cross-talk, and are significantly more expensive than conventional photomultiplier tubes.

Silicon PIN photodiodes, on the other hand, have stable gain, require less than 100 V power supplies, are insensitive to magnetic fields, have high quantum efficiency (50% – 80% in the visible spectrum), can be made in small sizes (minimum dimension of the optical surface is approximately 100 μm, minimum depth is approximately 2 mm including substrate), are relatively inexpensive (<\$10/cm^2), and can be made in close packed arrays with small dead area and crosstalk. However, PIN photodiodes are unity gain devices and have low quantum efficiency at violet and ultraviolet wavelengths, which makes them very sensitive to electronic noise and limits the energy and timing resolution when measuring gamma radiation with scintillators.

CsI(Tl) scintillator is frequently used with photodiodes for gamma detection because of its high light output (64,000 photons/MeV) and appropriate emission wavelength (540 nm). However, it is difficult to detect gamma rays with energy above ~200 keV with good spatial resolution in CsI(Tl) because its relatively low density (4.5 g/cc) and atomic number limit its attenuation length and photoelectric fraction (2.4 cm and 22% respectively at 511 keV gamma energy).

LSO is an attractive alternative to CsI(Tl) because its high density (7.4 g/cc) and atomic number give it significantly shorter attenuation length and higher photoelectric fraction (1.2 cm and 34% respectively at 511 keV gamma energy) [1]. While its light output (25,000 photons / MeV) is less than that of CsI(Tl) and its emission spectrum is not as good of a spectral match to silicon photodiodes (the emission peak is at 420 nm), it has significantly higher light output than other high density scintillators such as BGO ($Bi_4Ge_3O_{12}$) or GSO (Gd_2SiO_5:Ce). In addition, its short decay time (40 ns) enables a more accurate timing signal to be generated. Thus, it is possible that LSO scintillator crystals read out by photodiodes will have advantages over more conventional systems in some applications. This paper explores the energy and timing resolution obtainable with such a detector system.

2. LSO "INTRINSIC" RESOLUTION

The LSO crystal used for this work is 3x3x22 mm^3 with a smooth polish on all six sides. All surfaces except for one 3x3 mm^2 face are covered with several layers of Teflon tape to form a white reflecting coating. The "intrinsic" energy resolu-

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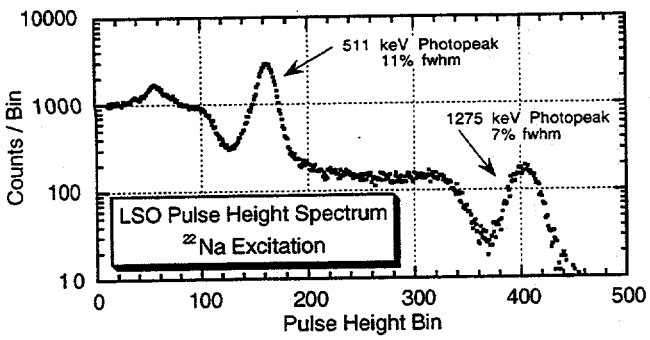

Figure 1: Pulse height spectrum of the 3x3x22 mm LSO crystal coupled to a photomultiplier tube when excited with a ^{22}Na source.

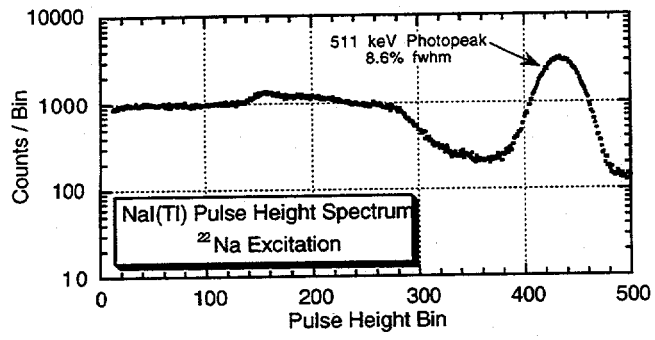

Figure 2: Pulse height spectrum of a calibrated NaI(Tl) crystal coupled to a photomultiplier tube when excited with a ^{22}Na source.

tion of the crystal is measured by coupling it to a Hamamatsu R–878 photomultiplier tube and measuring the ^{22}Na excited gamma ray spectrum, shown in Figure 1. The LSO crystal is replaced with a NaI(Tl) crystal with calibrated light output and the experiment repeated, with the resulting spectrum shown in Figure 2. By comparing the relative positions of the 511 keV photopeaks in the two materials and normalizing to the calibrated NaI(Tl) light output value of 38,000 photons/MeV [2], the light output of this LSO crystal is measured to be 14,100 photons/MeV. This value is significantly less than the 28,500 photons/MeV previously quoted for LSO [1] and deserves comment. First, when the light output of this crystal is measured with a more favorable light collection geometry, a value of 23,800 photons/MeV is obtained, thus illustrating the importance of light collection efficiency. In particular, the light collection efficiency for the long, thin geometry of this crystal is 60–75% of a cubic geometry (for both BGO and LSO). In addition, the light output of LSO varies from crystal to crystal, typically from 20,000 to 25,000 photons/MeV.

The full width at half maximum (fwhm) of the 511 keV and 1275 keV photopeaks are 11% (57 keV) and 7% (90 keV) respectively. While this is poorer resolution than is expected based on photon counting statistics, it is typical for LSO and has been noted previously [3]. While it has been suggested that this effect may be due to non-linear energy response [3], it is also possible that the effect is due to clustering of the cerium dopant leading to spatially dependent luminous efficiency on a microscopic scale. Alternatively, the light collection efficiency

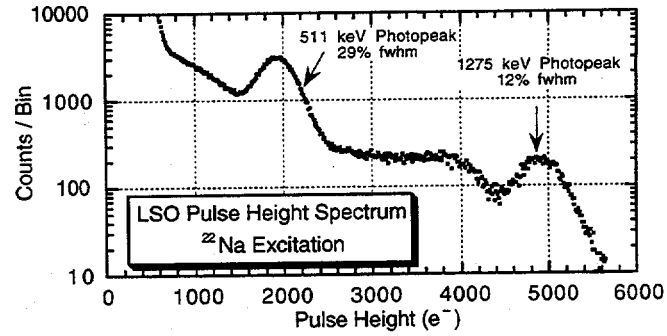

Figure 3: Pulse height spectrum of the 3x3x22 mm LSO crystal coupled to a photodiode when excited with a ^{22}Na source.

is quite sensitive to the surface preparation and reflector material, which may lead to a spatially dependent light collection efficiency and so degraded energy resolution.

The "intrinsic" timing resolution was measured by exciting a barium fluoride scintillator crystal coupled to a Hamamatsu R–2059 photomultiplier tube with one annihilation photon from a ^{68}Ge source and the LSO crystal coupled to another R–2059 photomultiplier tube with the other 511 keV photon. Output pulses from both photomultiplier tubes were converted into logic signals with a Tennelec TC-222 constant fraction discriminator (CFD), and the time difference between the two signals was digitized by a Tennelec 862 time to amplitude converter and a LeCroy 3512 analog to digital converter. The resulting coincidence timing resolution is 0.6 ns fwhm, consistent with previous measurements [4].

3. PIN PHOTODIODE CHARACTERISTICS

The PIN photodiode used is a Hamamatsu S-2506 (2.77 mm square active area, 100 μm depletion thickness) mounted in a special package to allow close coupling to the scintillator crystal. When operated at room temperature (+25° C) with an 80 V bias, this photodiode has a capacitance, dark current, and series resistance of 8.1 pF, 140 pA, and 104 Ω respectively. A low noise charge sensitive preamplifier is used to amplify the photodiode output and a 1.0 pF capacitor at the input of the preamplifier is used to couple a test pulse voltage to the system and obtain the conversion factor relating output voltage to number of electrons input. The amplifier is operated with a 4 μs peaking time, under which conditions the photodiode / amplifier combination has a noise of 370 electrons (e^-) fwhm.

4. PULSE HEIGHT SPECTRUM

The LSO crystal is then coupled to the photodiode, the detector module excited with 511 keV and 1275 keV photons from a ^{22}Na source, and the pulse height spectrum shown in Figure 3. Photopeaks for the 511 keV and 1275 keV gamma rays are observed at 1940 and 4910 e^- respectively, leading to an observed signal of 3.8 e^-/keV energy deposit. This is slightly less than the signal expected with an LSO light output of 14,100 photons/MeV, a light collection efficiency

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of 50%, and a photodiode quantum efficiency of 50% at the 420 nm peak of the LSO emission spectrum.

The widths of the 511 keV and 1275 keV photopeaks are 29% and 12% fwhm respectively (149 keV in both cases). Dividing the 370 e^- fwhm electronic noise by the 3.8 e^-/keV energy to electron conversion yields an energy independent noise contribution of 100 keV fwhm. Adding this electronic noise (in quadrature) to the "intrinsic" energy resolution measured in Section 2 gives predicted widths of 23% and 11%, which are slightly lower than those observed.

5. Timing Spectrum

The timing spectrum in Figure 4 was acquired by replacing the LSO / photomultiplier tube detector in the system described in Section 2 with the LSO / photodiode detector assembly. In this measurement an amplifier with a 100 ns rise time and a 2 μs fall time was used, and the amplified signal was passed through a timing filter amplifier with a 20 ns shaping time and a timing signal generated whenever the detector observed the equivalent of >250 keV energy. In this configuration (with the detector excited by 511 keV photons), a timing signal with 35 ns fwhm time jitter is produced. The dependence of the timing jitter on gamma ray energy was tested by substituting a ^{22}Na source (which produces three photons in coincidence – a 1275 keV gamma and a back-to-back pair of 511 keV gammas) and setting the CFD threshold in the LSO / photodiode detector to an equivalent of 900 keV energy. The resulting timing distribution, shown in Figure 5, shows the a timing signal with 25 ns fwhm timing jitter is produced when the detector is excited with 1275 keV photons.

6. Discussion

The electronic noise in the photodiode / amplifier dominates the performance of an LSO / photodiode detector to perform gamma ray spectroscopy. In the configuration described herein, this noise is equivalent to approximately 100 keV fwhm. This implies that the minimum energy gamma ray that can be detected is approximately 200 keV, and that the energy resolution is roughly 150 keV fwhm, independent of gamma ray energy, for energies less than 1 MeV. This energy resolution is 50% above the energy resolution requirement for PET detectors of approximately 100 keV fwhm for 511 keV gammas [5].

This noise equivalent energy can be reduced significantly with an improved photodiode. Reducing the series resistance to <20 Ω would effectively eliminate the Johnson noise due to this resistance and reduce the noise to approximately 80 keV. Reducing the capacitance to 3 pF by using a 300 μm depletion thickness photodiode would lower the noise fwhm to 65 keV, and reducing the capacitance to 0.5 pF by using silicon drift photodiodes [6] or high band-gap photodetectors such as HgI_2 [7] or InI [8] would lower the noise fwhm to 55 keV. In this case, the "intrinsic" energy resolution of LSO would be the limiting factor for gamma ray spectroscopy.

On the other hand, a larger scintillator volume is frequently desired to increase the sensitivity of the detector to the gamma

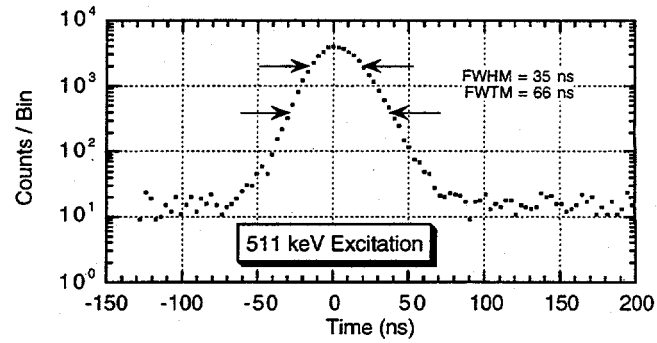

Figure 4: Coincidence timing spectrum for the LSO / photodiode detector when excited with 511 keV photons.

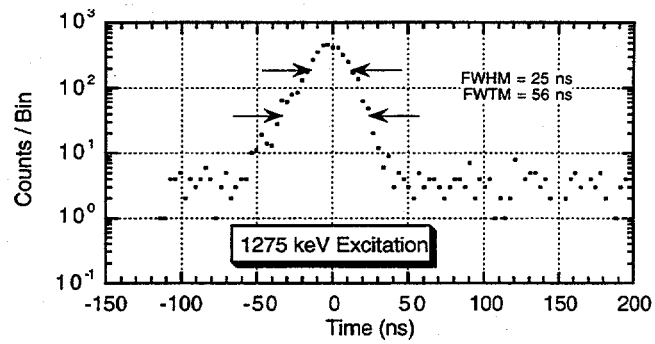

Figure 5: Coincidence timing spectrum for the LSO / photodiode detector when excited with 1275 keV photons.

field that it samples. If the size of the scintillator is increased, the size of the photodiode must also be increased to maintain good optical coupling. The photodiode capacitance increases linearly with surface area and the electronic noise is approximately linear with detector capacitance, so the electronic noise for a photodiode of arbitrary surface area can be roughly estimated as 1000 keV/cm^2 (based on these measurements with a 100 μm depletion thickness Hamamatsu S-2506 photodiode).

The photodiode and amplifier used for this measurement are not well suited for timing measurement. The accuracy of the timing signal is proportional to the signal to noise ratio (a large component of the noise scales like the square root of the bandwidth) divided by the rise time (which is proportional to the bandwidth) [9]. Thus, the 100 ns rise time minimum of the low noise charge sensitive preamplifier imposes a significant limit on the timing resolution. In addition, reducing the noise factors described above (the Johnson noise due to the 100 Ω series resistance and the detector capacitance) could potentially improve the timing resolution by a factor of four. These improvements would probably bring the detector module below 10 ns fwhm, which is slightly greater than the 5 ns fwhm timing requirement for a PET detector [5].

Finally, the signal to noise ratio can be improved by increasing the light collection efficiency from the LSO crystal, either through optimization of the reflector and surface finish or the shape of the crystal itself. For instance, an increase of 30%–50% is possible by using a scintillator crystal with cubic (rather than a long, thin) geometry.

7. CONCLUSIONS

A detector module that uses a silicon photodiode to read out an LSO scintillator crystal has been characterized in terms of gamma ray energy resolution, timing accuracy, and conversion factor from gamma energy to number of electron-hole pairs produced. For the detector characterized, this conversion factor is 3.8 e^-/keV and the energy resolution is dominated by the electronic noise, which is equivalent to approximately 100 keV fwhm. The timing accuracy is 35 ns fwhm for 511 keV photons and 25 ns fwhm for 1275 keV photons. With the present photodiode, the energy and timing resolution are insufficient for PET detector modules. Improvement in photodiode technology can improve both the energy and timing resolution significantly, possibly to the point where a PET detector module could be formed from LSO crystals coupled to photodiodes.

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