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Reflectivity quenching of ESR multilayer polymer film reflector in optically bonded scintillator arrays

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ABSTRACT

The 3M-ESR multilayer polymer film is a widely used reflector in scintillation detector arrays. As specified in the datasheet and confirmed experimentally by measurements in air, it is highly reflective (>98%) over the entire visible spectrum (400–1000 nm) for all angles of incidence. Despite these outstanding characteristics, it was previously found that light crosstalk between pixels in a bonded LYSO scintillator array with ESR reflector can be as high as ~30–35%. This unexplained light crosstalk motivated further investigation of ESR optical performance. Analytical simulation of a multilayer structure emulating the ESR reflector showed that the film becomes highly transparent to incident light at large angles when surrounded on both sides by materials of refractive index higher than air. Monte Carlo simulations indicate that a considerable fraction (~25–35%) of scintillation photons are incident at these leaking angles in high aspect ratio LYSO scintillation crystals. The film transparency was investigated experimentally by measuring the scintillation light transmission through the ESR film sandwiched between a scintillation crystal and a photodetector with or without layers of silicone grease. Strong light leakage, up to nearly 30%, was measured through the reflector when coated on both sides with silicone, thus elucidating the major cause of light crosstalk in bonded arrays. The reflector transparency was confirmed experimentally for angles of incidence larger than ~60° using a custom designed setup allowing illumination of the bonded ESR film at selected grazing angles. The unsuspected ESR film transparency can be beneficial for detector arrays exploiting light sharing schemes, but it is highly detrimental for scintillator arrays designed for individual pixel readout.

1. Introduction

Scintillation detectors used nowadays in PET imaging must be designed to achieve high detection efficiency and high spatial resolution. However, these two parameters impose conflicting constraints on the choice of scintillator geometry, requiring long crystals for the former and small cross-section for the latter, which results in needle-like crystals with a high aspect ratio. Most current PET detector designs exploit a light-sharing scheme where the position of interaction is determined through the dispersion of the scintillation light among several photodetectors. On the contrary, in a one-to-one coupling scheme, the scintillation light must be constrained within the interaction pixel in order to be detected by the corresponding sensing pixel. In this case, any loss of signal to adjacent pixels must ideally be avoided, and efficient piping of the light to the photodetector becomes crucial.

In closely-packed arrays of long and narrow crystals, the scintillation light collection can be dramatically degraded by imperfect reflection conditions on the lateral faces. Minor deficiencies in optical adhesive transmittance or reflector efficiency were shown to be severely exacerbated by the numerous reflections occurring before photons reach the photodetector. Depending on the nature and opacity of the reflector, there is also a possibility that scintillation light propagates into adjacent pixels, decreasing the output signal from the pixel of interaction and increasing the probability of mispositioning. Such light crosstalk effects were found to account for as much as ~30–35% of the signal in LYSO arrays, when the Vikuiti Enhanced Specular Reflector (3M-ESR) film was used as reflector [1–3].

The 3M-ESR multilayer film is widely used as a reflector in PET detectors [4–15]. In most of these applications, the reflector is quoted as a 65-µm thick high-reflectivity specular film, with >98% reflectivity over the entire visible spectrum for all angles of incidence, as specified in the 3M datasheet [16]. Since it is often the reflector of choice in detector arrays, the film was investigated in [10,17] to characterize its spectral and angular reflectivity, confirming its excellent optical

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performance. However, data are always reported for measurements taken in air, as opposed to scintillator arrays where the reflector film is often in optical contact with adhesive to ensure the array's structural integrity. Since high light crosstalk was observed in tightly packed crystal arrays, it is relevant to verify whether the 3M-ESR reflectivity remains unaffected when bonded into crystal arrays.

In this study, the 3M-ESR transparency was investigated by theoretical simulations, experimental measurements and in real-life detector assembly conditions, where the reflector is bonded with an optical compound.

2. Materials and methods

2.1. AFM imaging

Atomic force microscopy (AFM) images of the 3M-ESR film cross section were obtained in order to assess its multilayer structure. A small sample of reflector was completely immersed in epoxy, then cured, and the edge was exposed by polishing the epoxy. In this work, the microscope (Veeco Dimension 3000 with Nanoscope IIIa controller) was operated in tapping mode to obtain topographic and phase contrast images. In tapping mode AFM, a piezoelectric element oscillates a cantilever which has a small tip fixed on one of its end [18]. A detector measures the deflection of the oscillating (tapping) cantilever when the tip is displaced over the surface of a sample [19]. Regions of varying stiffness or with different adhesion properties can affect the phase of the AFM probe relative to its resonant frequency, enabling the phase contrast imaging mode [20]. Unlike the standard topographic imaging mode, the different thin layers of the multilayer film thus can be distinguished in phase contrast mode.

2.2. Simulations

As the 3M-ESR multilayer polymer structure and exact composition are proprietary, simulations of the film can be challenging. Based on details given in [21,22] about giant birefringent optics in multilayer films and on the AFM images of the 3M-ESR film, analytical calculations were performed with MATLAB to obtain simulated reflectivity data, as a function of both the wavelength and the angle of incidence of the light impinging on the film.

The Monte Carlo software Geant4 [23] was used to simulate 511-keV photon interactions occurring in parallelepipedic $Lu_{1.9}Y_{0.1}SiO_5$ (LYSO) scintillator. The cross section of the crystal was uniformly irradiated at normal incidence with the 511-keV photons until 25,000 photoelectric events occurred anywhere in the crystal volume. The angular distribution of the generated scintillation photons (LYSO light yield of 28,000 photons/MeV) on the lateral reflectors was assessed. The angle of incidence was recorded for each scintillation photon impinging on a reflector after crossing a layer of adhesive. The surfaces of the scintillator were defined as almost perfectly polished with a parameter $\sigma_\alpha = 0.02$ in Geant4 [24]. Two adhesive types with ideal (100%) and low transmittance (~70% through 25 μm at 400 nm, based on Dymax OP-20 optical adhesive [25]) were tested since the adhesive transparency has an important impact on light collection [26].

2.3. Measurements

Fig. 1 displays six configurations that were used to assess the 3M-ESR transparency. This was carried out by reading the scintillation signal from a crystal with an avalanche photodiode (APD) through the reflector covered or not with layer(s) of silicone grease (SiG). The top and lateral faces of a 3×3×3 mm^3 LSO crystal were wrapped in several layers of Teflon tape to ensure maximum light recovery. In configuration (a), no optical coupling compound was used. Silicone grease (Bicron BC-630, n=1.47) was applied on the nude face of the crystal for configurations (b), (d) and (f), and on the back of the 3M-ESR (in contact with the APD) for configurations (e) and (f).

A ^{68}Ge (511 keV) radioactive source was used to irradiate the crystal. Energy spectra were obtained using a c7532 UV-enhanced APD from Excelitas Technologies (Vaudreuil-Dorion, Canada) operated at a gain of 150 and connected to a low noise charge-sensitive preamplifier contributing approximately 400 rms electrons noise with 0 pF at the input along with an ORTEC 452 spectroscopy amplifier with a shaping time of 250 ns. All measurements were performed at ambient temperature (21.5 ± 0.5 °C) and repeated multiple times to ensure reproducibility. A new sample of the 3M-ESR reflector was used between each measurement that involved SiG on at least one of its sides. The reflector was tested face-up and face-down in order to check for a possible influence of the film orientation on its transparency. This method integrates all possible incident angles of scintillation photons since the light is emitted isotropically in the crystal following radiation interactions.

A second set of measurements was carried out to characterize the 3M-ESR reflector transparency as a function of the light angle of incidence. A long and narrow LYSO crystal had one of its small face cut at an angle of 50°, and was then mechanically polished to optical quality. A 3M-ESR sample was placed underneath the crystal and above a photomultiplier tube (PMT) with silicone grease coupling on both sides of the reflector, as in configuration (f) of Fig. 1. The light from a pulsed light emitting diode (LED) mounted on a scale protractor was collimated through a pinhole to impinge on the cut face of the crystal at a desired angle θ_1 (see Fig. 2). The light being refracted into the crystal at θ_2, then into the optical grease layer at θ_3, finally impinges on the reflector at an angle θ_4. This setup allowed us to span a wider angular range not normally available with light incident from air. Snell's law ($n_{LYSO} = 1.82$ and $n_{SiG} = 1.47$) was used to calculate the light refractions, but dispersion of the materials refractive index (RI) was neglected. The light crossing the reflector was read by the PMT (Photonis XP1911) biased at 1200 V, giving an assessment of the film transparency as a function of the light angle of incidence. The signal amplitudes were measured using an oscilloscope. Five different LED colors (white, blue, green, amber, and red) were tested, and their emission spectra are displayed in Fig. 3. The experimental setup was optically isolated from ambient light, and all measurements were repeated multiple times to ensure reproducible results.

When light is refracted at a boundary between two materials with different RI, there is always a fraction of the intensity that is not transmitted, hence reflected, as described by the Fresnel equations. This reflected fraction is determined by the RI of the two materials, the polarization state of the light, and the light angle of incidence at the interface. Assuming unpolarized LED light, the fraction of reflected light at each interface was estimated using Fresnel equations to compensate for this effect that becomes significant at large angles of incidence. To minimize the introduction of back reflected light on the extraction face (LYSO/SiG interface) and the 3M-ESR in this setup, all crystal faces except the oblique entrance face and the extraction face were covered with black paint. Error propagation through each step of the calculations was carried out to estimate uncertainties in angles of incidence and the measurements were repeated multiple times to determine the standard deviation error in the measurement of the transmitted light through the 3M-ESR film.

3. Results

3.1. AFM images

Two AFM images are presented in Fig. 4, showing a cross section through the entire reflector thickness of 65 μm and a zoom at higher magnification (5×5 μm^2). On the lower resolution topographic contrast image, two distinct regions about 22 and 32 μm thick can be distinguished. The thin sub-μm multilayer structure of the film