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Coupling between Plastic Scintillators and Light Fibers for Remote Detection of X-rays

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Abstract

Plastic scintillators can be coupled to light fibers to make small, simple, and inexpensive x-ray detectors. These detectors have been developed for use at the Nevada Test Site (NTS) for the remote detection of x-rays. Light produced in the scintillator can be transmitted by the fiber for several hundred meters to a photodetector, which is usually a streak camera or a photomultiplier tube. The use of a streak camera allows many channels to be recorded simultaneously.

A parameter study has been done to measure the sensitivity of these detectors as a function of scintillator geometry, type of scintillator, coupling geometry, and x-ray energy. The results can be qualitatively explained by a simple geometric theory.

A recent use of these detectors at NTS was the measurement of an x-ray spectrum. System performance for this measurement will be reviewed.

Introduction

Diagnosing x-rays from an underground nuclear test is complicated by the requirement that the recording station be several hundred meters from the site of the measurement. In the past these measurements have mainly been done by using x-ray detectors connected to long, high-bandwidth, expensive coaxial cables. In order to reduce the cost and increase the number of data channels a simpler system consisting of a plastic scintillator coupled to a light fiber has been developed and used successfully at distances over 500 meters.

Figure 1. An x-ray detector consisting of a light fiber coupled to a plastic scintillator.

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The geometry of the system is illustrated in Figure 1. A light fiber is butt-coupled to a plastic scintillator of length L, width W, and depth D, with the fiber pointed at right angles to the direction of the x-rays in order to enhance the light collection efficiency. No coupling grease was used at the interface between the fiber and the scintillator.

The amount of light collected in the fiber can be estimated by a simple geometric theory. Begin by assuming that W and D are infinite. Let I_0 be the light emitted per unit volume in the scintillator, α be the self-absorption coefficient of the scintillator, and A_c be the area of the light fiber core. The light emitted from a point in the scintillator can enter the light fiber only if the point is within the acceptance cone of the light fiber. The fraction F of light from such a point that enters the fiber is

$$F = \frac{A_c \cos \theta}{4\pi r^2} e^{-\alpha r} \quad (1)$$

where r is the distance from the point to the fiber and θ is the angle at which the light enters the fiber core. Let θ_c be the half-angle of the acceptance cone. The light arriving from all points in the scintillator is then approximately

$$I = I_0 \int_0^L \int_0^{\theta_c} \int_0^{2\pi} e^{-\alpha r} \frac{A_c \cos \theta}{4\pi r^2} r^2 \sin \theta d\phi d\theta dr \quad (2)$$

The approximation is equivalent to making the flat end of the scintillator a spherical surface with radius of curvature L and is valid for small θ_c . (The integral can be done without this approximation but the algebra is more complicated.) Integration of (2) yields

$$I = I_0 \frac{A_c}{4\alpha} (1 - \cos^2 \theta_c) (1 - e^{-\alpha L}) \quad (3)$$

which for $\alpha L \ll 1$ reduces to

$$I = \frac{1}{4} I_0 A_c L (1 - \cos^2 \theta_c) \quad (4)$$

This result also holds when W and D are finite if one assumes total internal reflection off the walls of the scintillator. Consider the case where the acceptance cone of the fiber is clipped by the walls of the scintillator. At first it seems that it is necessary to change the integration region of Equation 2. However, for every point in the integration region that now lies outside the scintillator, there is by symmetry a point inside the scintillator that has an increased contribution to the integral because of internal reflection from the walls. Thus, Equations 2 through 4 are still valid and the amount of light collected by the fiber is independent of the width and depth of the scintillator and directly proportional to the length.

This derivation assumes that I_0 is uniform throughout the scintillator. Actually, I_0 is highest on the face where the x-rays enter the scintillator. For small θ_c this does not have much effect on the integral, and I_0 can be assumed uniform and given by

$$I_0 = \phi A \epsilon / D \quad (5)$$

where ϕ is the energy flux per unit area falling on the scintillator, A is the fraction of x-ray energy absorbed in the scintillator, and ϵ is the intrinsic efficiency of the scintillator. A convenient expression for the sensitivity η of this detector is the ratio of the light energy I in the fiber to the energy flux ϕ .

$$\eta = I / \phi \quad (6)$$

which has the units of area.

Detector Characterization

Several measurements were performed to obtain some experimental results for the sensitivity of these detectors. The source of x-rays used for these measurements was the low-energy x-ray facility (LEX)⁴ at LLNL. This facility produces unpolarized x-rays in the range from 1.5 to 8 kev. The x-ray beams have a spectral purity greater than 95% and have an intensity of about 10^8 x-rays/cm²-sec. A high resolution lithium drifted silicon Kevex

detector that has a quantum efficiency of 1 to within 2% was used to measure the absolute intensity of the beam.

The scintillator detectors were mounted in the x-ray beam directly behind a .002-inch beryllium vacuum barrier. Graded index, 50 micron core diameter fibers with a numerical aperture of 0.2 were used in the experiment. The fibers went from the scintillators to an RCA GaAs PM tube (type C31034-02) which was cooled to -30°C to reduce the dark current. The PM tube was operated in a photon counting mode to obtain maximum sensitivity.

The first scintillator material to be investigated was Bicron Corporation's BC-430 (similar to NE-108). The sample size was 14 mm x 20 mm x 1.4 mm (L x W x D). The sensitivity of the detector was measured at several energies between 1.5 and 8 keV and the results are shown plotted in Figure 2. If Equations 4-6 are used to calculate the intrinsic efficiency of BC-430, the efficiency shows an increase with increasing photon energy. This increase is consistent with a square root dependence on energy for the scintillator efficiency as reported by Lyons, et. al.^{2,3} However, the efficiency at 8 keV is only 1.2% which is too small. We conclude that the simple geometric theory overestimates the true light collection efficiency, but that it is good for rough calculations.

We next investigated the effect of length, width and depth. Changing the width from 20 mm to 1.5 mm had no effect on the sensitivity indicating that light could indeed be internally reflected in the scintillator. The effect of changing the length is shown in Figure 3. The sensitivity is roughly proportional to length as would be predicted by Equation 4.

Figure 2. Sensitivity of the detector as a function of energy.

Figure 3. Sensitivity of the detector as a function of length.

BC-430 is a bright scintillator, but with a response time of 12 nanoseconds (FWHM) it is rather slow. Most fast plastic scintillators emit blue light which cannot be transmitted over long distances with fiber optics. As a result, we investigated several possibilities in the search for a bright, fast, red-emitting plastic scintillator. Following the work of Lutz, et. al.⁴ we tried using different concentrations of the laser dyes DCM and C-480 in a polystyrene base.

DCM is Kodak Dye #14567 or 4-dicyanomethylene-2-methyl-6-p-dimethylamino stryl-4H-pyran. C-480 is 2,3,5,6-tetrahydro-8-methyl-2H-quinolin-9(9H)-one. These were mixed in various concentrations and dissolved in styrene. The plastic was polymerized in a relatively quick process developed at LLNL². Table 1 contains the results of this investigation. The table shows that it is possible to have a fast red-emitting plastic scintillator but at the expense of some loss of light output.

Table 1

Composition	η (at 8 keV) (mm ²)	Time Response (FWHM ^b)	λ_{peak}
BC-430	7.8×10^{-7}	12 ns	570
.125 M DCM	7.5×10^{-8}		
.063 M DCM	8.4×10^{-8}	2 ns	630
.013 M DCM	1.1×10^{-7}		
.05 M DCM and .16 M C-480	2.1×10^{-7}		
.025 M DCM and .08 M C-480	3.1×10^{-7}	3 ns	610

Application

These type of detectors were recently used at NTS to measure an x-ray spectrum. Figure 4 shows a schematic diagram of the experiment. X-rays were reflected from an x-ray mirror onto an x-ray diffraction crystal in the same manner as described by Woodruff¹. Eighty-four BC-430 scintillator detectors were used to sample the x-ray spectrum. Figure 5 is a picture of the scintillators as they were mounted in the detector. These were connected to 500 meter lengths of graded index fiber with 50-micron core diameter. Each fiber was then fed into one of four streak cameras. The signals observed from the experiment were clean and strong showing that this type of detector is practical for use in NTS experiments.

Figure 4. Schematic diagram of experiment.

Figure 5. Picture of segmented scintillator detector.

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