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Gamma-Ray to Cerenkov-Light Conversion Efficiency for Pure-Silica-Core Optical Fibers

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Abstract

We have determined experimentally the absolute gamma-ray to Cerenkov-light conversion efficiency for pure-silica-core optical fibers in the vicinity of metallic Compton-converter slabs. To measure the energy dependence of this process, we used ^{60}Co and ^{24}Na radiation sources. The results show how the conversion efficiency varies with Compton-converter material, thickness, angle of the fiber, and fiber-converter distance. We also performed computer calculations of conversion efficiency. This method employs an electron-photon transport code named SANDYL together with analytical calculations of Cerenkov-light generation. We compare the results of these calculations with experimental results.

Introduction

Pure-silica-core optical fibers are used by the Lawrence Livermore National Laboratory (LLNL) and the Los Alamos National Laboratory (LANL) in high-bandwidth analog diagnostic systems for gamma rays, in the Nuclear Testing Program at the Nevada Test Site. An intense gamma-ray signal emitted from an exploding nuclear device is permitted to strike a "thin" slab of material, producing Compton electrons. The electrons pass through an optical fiber, which consequently generates a Cerenkov-light signal. The light is then transmitted via a second fiber to a remote location for recording (Fig. 1). This diagnostic system is described in more detail by another paper in this session.¹

Both LLNL and LANL have ongoing programs to optimize and characterize this optical-fiber diagnostic scheme. In these programs, ^{60}Co and ^{24}Na gamma-radiation sources are used in the laboratory to determine absolute gamma-ray to Cerenkov-light conversion efficiency and to investigate the effects of different fiber types and geometries. These characteristics are also investigated by computer calculations. The work described in this paper was done as part of the ongoing programs.

Figure 1. Diagram of a field diagnostic in which Cerenkov light is produced in an optical fiber.

Basic Experimental Arrangement

Figure 2 shows the basic setup. The ^{60}Co source presently has an activity of about 2700 Ci, which results in a gamma-ray flux of about 0.75 rad/s or about 1.5×10^{10} MeV/cm²/s at an experimental distance of 1 m. Typically, lead collimators 2.5 to 5 cm in diameter and 20 cm long are positioned between the source and the Compton-converter plate, with the exit 63.5 cm from the source center. Since the source diameter is about 2.5 cm, a penumbra diameter up to 9.5 cm must be allowed for at the converter. A pair of magnets is placed just beyond the collimator exit to deflect any Compton electrons emitted from the source or collimator assemblies. To eliminate background light, the experiment is covered and the fiber is inserted into light-tight conduit between the source room and control room where the detection system is located.

All measurements of Cerenkov-light signals are made using photon-counting techniques. The photomultiplier tube is an RCA C31034 with a gallium arsenide cathode in a cooled housing. The optical input allows for use of a bandpass or neutral-density filter. Counting electronics consist of an EG&G Ortec (Oak Ridge, Tenn.) model 450 amplifier, an EG&G Ortec model 551 single-channel analyzer, and a Canberra (Meriden, Conn.) model 1776 counter. Typical signal count rates within this system range from about 10 to more than 1000 counts/s, while the photomultiplier background rate is about 1 count/s.

Absolute Conversion Efficiency for ^{60}Co Gamma Radiation

A ^{60}Co gamma-ray source has several advantages in calibrating and characterizing Cerenkov-light-producing fiber-optic diagnostics used in nuclear testing. The five-year half-life minimizes the effort required to correct for intensity changes. The 1.17- and 1.33-MeV photon energies are similar to those measured for exploding nuclear devices. The continuous nature of the cobalt source permits the use of slow but sensitive optical detection systems. For pure-silica-core fibers, the gamma-ray flux level is insufficient to cause fiber damage.

The absolute calibration scheme uses four measurement steps, as shown in Fig. 3. The geometry for all the steps is the same except for the changes described below. At the input end of the fiber to be measured, a quartz-iodine light source is attached to a filter box. The box has a collimating lens; three slots for filters; a diffuser; and at the output end, a bulkhead feedthrough for the fiber connection. The filter slots are angled at about 2° to prevent light reflected off filter faces from reaching the diffuser. About 0.5 m beyond its input end, the fiber passes through the gamma-beam path, where it is attached to the Compton-converter plate. Within an additional 0.5 m, the fiber is wrapped around a mode-stripping mandrel and then enters the protective conduit.

In step 1 of the measurement, light is transmitted through a bandpass filter placed in the filter box and strikes the diffuser, which is intended to fill all transmission modes of the fiber. The optical power transmitted by the fiber is input to a calibrated United Detector Technology (San Diego, Calif.) PIN photodiode of sensitivity S_{PD} , and its current output i_i is measured with an electrometer. This step measures the absolute light power P_i exiting the fiber at the wavelength interval determined by the filter:

$$P_i = \frac{i_i}{S_{PD}} \quad (1)$$

Figure 2. Diagram of the experimental setup for measuring Cerenkov-light signals.

Figure 3. Sequence of steps in measuring the absolute conversion efficiency of gamma rays to Cerenkov light.

Step 2 is like step 1 except that the light is attenuated by neutral-density filters with transmission T_{ND} placed in the filter box, and the fiber output P_2 is directed to the photomultiplier detector system. This generates the absolute sensitivity S_{PM} of the photomultiplier system at its optical input:

$$S_{PM} = \frac{N_2}{P_2} \quad (2)$$

where N_2 is the number of counts recorded for a prescribed time, and where

$$P_2 = T_{ND}P_1 \quad (3)$$

Cerenkov light to be obtained in the fiber in step 4 below requires that the bandpass filter be moved to the photomultiplier input. This change in geometry can cause small changes in light transmission through the system. Step 3 repeats the step 2 measurement after the filter is repositioned at the photomultiplier, and the ratio of the two measurements, N_2/N_3 , provides an appropriate correction factor.

In step 4 the Cerenkov-light output power P_4 is measured when the converter and fiber are exposed to gamma radiation. The geometry is identical to that for step 3, with the light shutter closed and the cobalt-source shutter open:

$$P_4 = \frac{N_4 N_2}{S_{PM} N_3} \quad (4)$$

The absolute conversion efficiency S_c for gamma-ray flux to Cerenkov-light output for the fiber can now be determined:

$$S_c = \frac{P_4 \eta_{BF}}{\phi_{Co} \ell_F} \quad (5)$$

where ϕ_{γ} is the gamma-ray flux in $\text{MeV}/\text{cm}^2\cdot\text{s}$, and η_{eff} is a filter normalization factor which corrects the integral of the filter spectral-transmission function to give a sensitivity for a 1-nm band. l_1 is the effective length of fiber exposed to gamma radiation:

$$l_1 = \frac{(\text{source-to-fiber distance})(\text{collimator diameter})}{(\text{source-to-collimator-exit distance})(\sin \theta)} \quad (6)$$

where θ is the angle between the fiber axis (light-propagation direction) and the cobalt beam axis. The above equations can be combined to give:

$$S_c = \frac{N_4 \eta_{\text{eff}} T_{\text{ND}} \phi_1}{N_3 \phi_{\text{Co}} f_{\text{F}} S_{\text{FD}}} \quad (7)$$

The results of step 2, N_2 , cancel out in this equation. The measurement is still maintained in the sequence to verify that the N_2/N_3 factor does not vary greatly from a value of 1.

Table 1 summarizes the measurements for three optical fibers and four wavelengths. The numerical-aperture values given were measured with the step 3 fiber input geometry described above, and mode stripping was used. The strength of the light source did not permit bandpass filters to be used for these numerical-aperture measurements.

The ^{60}Co source suffers from internal Compton scattering, which causes significant low-energy gamma rays to be emitted. A uranium/graded-Z filter² was used to minimize this contribution. With the filter the average gamma-ray energy was about 1.1 MeV.

The uncertainty of the sensitivity data is estimated to be about 10%. Most of the individual uncertainties were of the order of 3%.

Effect of Compton-Converter Material on Efficiency

Cerenkov light is emitted within an optical medium at an angle θ relative to an electron path, where $\cos \theta = 1/\beta n$; β is the electron velocity and n is the refractive index. This requires that β be greater than $1/n$. For 1-MeV electrons and $n \approx 1.46$, $\theta \approx 43^\circ$.

The angular distributions at which Compton electrons are emitted are given by the differential Klein-Nishina cross-section for electrons.³ This indicates that the Compton electron flux will be peaked in the gamma-ray beam direction and that these electrons will have the highest energies. To capture the maximum amount of Cerenkov light, the fiber should be placed at a 43° angle with respect to the gamma-ray direction. For a Compton-converter plate of finite dimensions, however, the electrons will undergo scattering dependent upon the material type and thickness. Because low-Z materials produce less scattering, they can be used to maximize the number of electrons that will produce Cerenkov light within the fiber acceptance angle. At the same time, fewer electrons at other angles will help minimize the fiber radiation damage relative to light production.

Table 2 shows measurements made with several materials. The measurements confirm that low-Z materials produce the maximum amount of light. It should be noted that the fiber is also in the beam for all of these measurements. For the best measured material (beryllium), about 42% of the signal was derived directly from the fiber. This is due to Compton electrons produced in the fiber by gamma rays transmitted through the beryllium. For a larger-diameter Raychem fiber the value is about 54%.

Effect of Compton-Converter Thickness on Efficiency

A series of measurements using beryllium converter plates of different thicknesses determines the signal vs thickness relationship. The angle between the converter/fiber and beam is maintained at 45° . Figure 4 shows the results for a plastic-clad silica

Table 1. Summary of absolute gamma-ray to Cerenkov-light conversion efficiencies.

	Fiber type			
	Raychem VSC-200A	IT&T PSO-5 (PCS) Sample 1	IT&T PSO-5 (PCS) Sample 2	
Physical characteristic				
Core <i>D</i> diam (μm)	200	125	125	
Numerical aperture	~ 0.28	~ 0.39	~ 0.39	
Conversion efficiency S_c (J/MeV·cm ² ·nm) ^a , at wavelength λ				
	λ (μm)			
	570	16.8×10^{-27}	8.55×10^{-27}	—
	600	10.9×10^{-27}	5.02×10^{-27}	—
	700	7.28×10^{-27}	4.02×10^{-27}	—
	800	5.22×10^{-27}	2.84×10^{-27}	2.12×10^{-27}

^a Per centimeter of optical fiber.

Table 2. Relative Cerenkov-light production for different Compton-converter materials.

Converter material	Relative fiber output
1.6 mm beryllium	1.00
3.2 mm polyethylene (CH_2)	0.99
12.7 mm LiH	0.98
1.4 mm polystyrene (CH)	0.96
1.6 mm aluminum	0.86
0.8 mm copper	0.70
1.8 mm lead	0.67
PCS fiber only	0.42

Figure 4. Effect of Compton-converter thickness on Cerenkov light. The angle between the converter/fiber and the gamma beam is 45° .

Figure 5. Effect of the angle between the gamma-ray beam and fiber on Cerenkov-light output.

(PCS) fiber. For the gamma-ray and electron energies involved, a maximum signal was obtained for about a 2-mm thickness. Greater thicknesses caused a slight signal reduction due to gamma-ray absorption.

Effect of Beam-to-Fiber Angle on Efficiency

The Cerenkov-light signal strengths were measured for different angles of the fiber/converter with respect to the beam, and confirmed an optimum angle of about 45° . Figure 5 shows the results. Electron scattering, as already briefly discussed, can explain the flatter angular-sensitivity curve for brass compared with that for beryllium.

These data are for a PCS fiber having an unusually small measured numerical aperture, probably the result of poor termination procedures. The data were reproduced almost identically using the Raychem VSC-200A fiber with a numerical aperture of about 0.28.

Effect of Compton-Converter-to-Fiber Separation Distance

Most experiments were conducted with the fiber attached to the back side of the Compton-converter plate and centered in the gamma-ray beam. This experiment briefly investigated the effect of separating the fiber from the converter for both a low-Z material (beryllium) and a medium-Z material (brass). Figure 6 gives the results. For both measurements, the collimator diameter was 3.8 cm and the fiber and converter were at 45° . The results of this experiment would be expected to vary for different beam diameters.

Relative Efficiency of Cerenkov-Light Production with ^{24}Na and ^{60}Co

The ^{60}Co measurements provide optical-fiber sensitivities for the conversion of gamma rays to Cerenkov light at about 1 MeV only. To obtain sensitivities at a higher photon energy, we performed experiments using a ^{24}Na source. ^{24}Na decays with the emission of two gamma photons, one with an energy of 2.76 MeV and one with an energy of 1.38 MeV. To isolate the effect of the 2.76-MeV photon, ^{60}Co data are used, with appropriate interpolation, to subtract out the 1.38-MeV photon contribution.

The 2.76-MeV measurements were obtained with small, relatively-low-activity sources in a geometry which is less constrictive than the one used for the ^{60}Co measurements described above. The spectrum correction described earlier was not investigated or applied, but would be expected to be less critical.

The relative Cerenkov sensitivity S_K of an optical fiber for ^{60}Co (average photon energy 1.25 MeV) and the 2.76-MeV photon energy is approximately given by:

Figure 6. Effect of the distance between the fiber and converter on Cerenkov-light output.

Converter
CH (cladding) 0.1875 mm = 0.19 g/cm ²
SiO ₂ (½ core) 0.0625 mm = 0.14 g/cm ²
SiO ₂ (detector zone) 0.0001 g/cm ²
SiO ₂ (½ core) 0.0625 mm = 0.14 g/cm ²
CH (cladding) 0.1875 mm = 0.19 g/cm ²
Converter

Figure 7. Geometry simulating a Compton converter and fiber, used in computer calculations of the conversion efficiency of gamma rays to Cerenkov light.

$$S_R = \frac{3P_{Na}\phi_{Co}}{2P_{Co}\phi_{Na}} - \frac{m}{2}$$

(8)

where P is the power of the Cerenkov-light output of the fiber, ϕ is the source strength for the appropriate sources, and m is the relative fiber sensitivity at 1.38 MeV compared with 1.25 MeV. For ϕ values given in terms of MeV/cm²·s and for $m = 1.02$, the S_R value is determined to be about 1.2. A more precise formula is given in Ref. 4.

Computer Calculations of Gamma-Ray to Cerenkov-Light Conversion Efficiency

We calculated optical-fiber sensitivities using SANDYL, a Monte Carlo electron-transport code. SANDYL is a generalized three-dimensional transport code developed by Sandia National Laboratory, Livermore, based on theoretical and computational methods of Berger and Seltzer at the National Bureau of Standards.⁴ The code is used to calculate the electron flux as a function of energy and angle at the center of optical fibers. Assuming these fluxes to be uniform over the entire fiber core, Cerenkov-light production is calculated by analytic methods.

Figure 7 shows the slab geometry, which simulates a PCS fiber with a 125- μ m core diameter, and allows for gamma-ray-to-electron converters on both front and back surfaces. Gamma rays are incident at an angle θ to the front surface, and electron fluxes through the zone at the fiber center are tabulated. Electron fluxes were tallied in 11 energy groups between the threshold of 0.175 MeV and 10 MeV. Figures 8a and 8b show, respectively, the fluxes and light-output contributions from the electron-energy groups, as determined by an example calculation for 1.2-MeV gamma rays at 45° and a 5-mm-thick beryllium front slab converter.

Equation (9) is the analytic formula for the fraction F of the Cerenkov cone with angle α intercepted by a fiber with numerical aperture 0.21 (critical angle for total internal reflectance of 8°), and angle θ between the electron velocity and fiber.

Figure 8. Computer calculations of optical-fiber sensitivities, with the geometry shown in Fig. 7. (a) Electron flux. Each curve represents a different electron-energy range. (b) Cerenkov-light output at three electron-energy ranges. (c) Fraction F of the Cerenkov cone intercepted by a fiber with an 8° acceptance half-angle (numerical aperture is 0.21), at a 25.3° Cerenkov angle.

$$F = \frac{1}{\pi} \arccos \left[\frac{-\cos \theta}{\tan \alpha \sin \theta} + \frac{\sqrt{\frac{\cos^2 \theta}{\tan^2 \alpha} + \left(\frac{\sin^2 \theta - \cos^2 \theta \tan^2 8^\circ}{\tan^2 \alpha} + 1 \right)}}{\sin \theta} \right] \quad (9)$$

For a 25.3° Cerenkov angle, this formula gives the results shown in Fig. 8c.

We applied this method to calculate the light injected into a $50\text{-}\mu\text{m}$ transmission fiber with a numerical aperture of 0.21 by a PCS detector fiber large enough to fill all available transmission modes. For a typical fission gamma-ray spectrum incident at 45° on a 5-mm beryllium converter, the calculated result for light with an 800-nm wavelength is $1.95 \times 10^{-28} \text{ J/MeV} \cdot \text{cm}^2 \cdot \text{nm}$ per centimeter of fiber exposed. If this value is adjusted to correspond to a numerical aperture of 0.39 and a fiber core diameter of $125 \mu\text{m}$, $S_{\text{calc}} = 4.2 \times 10^{-27} \text{ J/MeV} \cdot \text{cm}^2 \cdot \text{nm}$ per centimeter of fiber. This compares with the values measured at the 800-nm wavelength.

Conclusions

We have determined the absolute gamma-ray to Cerenkov-light conversion efficiencies for pure-silica-core Raychem VSC-200A and IT&T PSO-F fibers, using a ^{60}Co radiation source and a geometry similar to that used in field applications. The relative efficiencies are also described, for changes in Compton-converter material, thickness, angle, and distance from the fiber. We found that efficiencies depend on the gamma-ray energy and on the particular fiber sample and the quality of its terminations. Computer calculations used to determine an efficiency for the PCS fiber produced a result similar to the measurements. This indicates that the physical processes occurring in the conversion of gamma-ray energy to Cerenkov-light energy for an optical fiber are reasonably well understood.

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