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Detection of Gamma Rays Using Plastic Scintillating Fibers

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Scintillating optical fibers have several advantages over the conventional materials used for radiation detection. The plastic scintillating fiber of Bicron model BCF-12 with an emission peak of 435nm has been used to detect ^{137}Cs gamma rays. Several types of sensors were constructed by packing in bundle forms different numbers of fibers into aluminum tubes, and tested to detect the gamma rays. The scintillation lights generated in the fiber bundle are transmitted through a low-attenuation fiber to a PMT. Optical coupling between the fiber bundle and the transmitting fiber is made either by direct alignment or by placing a small optical lens between them. In this paper, we report the pulse-height spectra obtained for ^{137}Cs gamma rays with various sensor types of two different optical couplings. Also presented is an analysis the proportionality between the total counts and the activities of 1.2μCi, 1.6μCi and 4.3μCi ^{137}Cs sources in the aspect of their usability for gamma ray detection. The effect of casing material for the sensor is also discussed. Our investigation suggests that the plastic scintillating fiber can be used to develop gamma ray detectors which can function in μCi-level gamma ray fields.

KEY WORDS: plastic scintillating fiber, plastic optical fiber, gamma ray detection, pulse-height spectra

I. Introduction

Optical fibers have been investigated for their potential use as sensor material in various nuclear applications. Comprehensive overviews of their potential use in nuclear environments can be found in literature.[1)] Optical fibers doped with scintillating components in the core have drawn special interests as potential use for nuclear radiation detectors. As a radiation detector, a scintillating optical fiber functions for dual purposes: scintillator (light emitter) and light transmitter. When a radiation interacts with the core material, scintillation occurs and resultant lights are transmitted through the fiber to an opto-electronic device such as a photomultiplier tube. Optical fiber sensors have several advantages as compared to other sensors of conventional material. No electric power is needed to the sensor part so that they are less susceptible to trouble in harsh environments such as underground or underwater. Optical fiber sensors cost relatively cheap to make them more suitable for a multi-point distributed radiation monitoring system. Furthermore, unlike the conventional scintillating counters they are not influenced by any magnetic field surrounding them.

Much effort has been exerted on applying scintillating optical fibers to developing probes for detecting neutrons and high-energy charged particles. Pacific Northwest Laboratory (PNL) have developed neutron sensing glass scintillating fibers, and they are now used in ribbon forms monitoring the inventory of sensitive nuclear materials.[2),3)] Also, there have been many research activities in Japanese research groups to apply scintillating optical fibers for radiation detection.[4),5)] Among these, the research work conducted by Maekawa [6)] is related to development of sensors using plastic scintillating optical fibers for detecting gamma and beta rays.

This work has been conducted to investigate the feasibility of using scintillating optical fibers for detection of gamma rays. We used the plastic scintillating fiber of Bicron model BCF-12 with the diameter of 1mm. Since single fiber may not be sensitive enough to detect gamma rays, we constructed several types of sensors by packing in bundle forms different number of fibers into aluminum tubes. The scintillation lights generated in the fiber bundle are transmitted through a low-attenuation fiber to a PMT. Optical coupling between the fiber bundle and the transmitting fiber is made either by direct alignment or by a small optical lens inserted between them.

The main concern of our study is to investigate some basic design parameters for a gamma ray detector. These include required number of fibers in the sensor, method of optical coupling between the fiber bundle sensor and the transmitting fiber, and the effect of casing material for the sensor. The optical fiber sensing system to be developed be deployed in the underground of a radioactive waste disposal site to monitor any leakage of gamma emitting radioisotopes. In this paper, we report the pulse-height spectra obtained for ^{137}Cs gamma rays with various sensor types of two different optical coupling methods. Also presented is analysis of the proportionality between the measured total counts and the activity of 1.2 μCi (4.44×10^4 Bq), 1.6 μCi and 4.3 μCi ^{137}Cs sources in the aspect of their usability for gamma ray detection. The effect of casing material for the sensor is also discussed.

II. The Experimental Method

The experimental setup used for this study is as shown in **Fig.1**. It consists of the sensor, a transmitting fiber, a photomultiplier tube (PMT)/preamplifier, a spectroscopy

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amplifier and a multi-channel analyzer (MCA). The sensor is constructed by packing into a cylindrical tube a different number of the plastic scintillating fibers of 1mm diameter and 100mm length. In order to determine a minimal number of fibers sensitive enough to the ^{137}Cs gamma rays, we constructed five types of the sensor with each having 3, 7, 13, 18 or 25 strands of the fibers. To investigate the effect of material for the sensor casing, we used stainless steel, aluminum and plastic PVC tubes with a thickness of 0.8 mm. The sensitive diameters of the sensors are 1.9mm, 3.1mm, 4.1mm, 4.8mm and 5.9mm, each corresponding in the same order to the number of the fibers used in the sensor as mentioned in the above. The plastic scintillating fiber is Bicron model BCF-12, which has a useful light emission spectrum between 390 and 570nm with a peak at 435nm. The core material is known to be polymethyl methacrylate (PMMA) with a density of 1.05 g/cm^3, for which the scintillating composition is not given.

Optical coupling between the sensor and the transmitting fiber is accomplished either by direct alignment or by placing a small lens between them as shown in **Fig.2**. The diameter of the lens is 6.0mm. The use of the lens was intended to collimate the lights from the sensor into the transmitting fiber. The fiber used to transmit the scintillation lights generated inside the sensor is a low-attenuation ESKA fiber with a nominal diameter of 3mm manufactured by Mistsubishi. The core is made of PMMA and is clad with a specially thin layer of fluorine polymer. This fiber is designed to provide higher transmission in the visible region of the spectrum. A detailed specification of the fiber is shown in the **Table 1.** To prevent the surrounding light from entering the fiber core through the side cladding, it is shielded by a thermal shrinkage plastic tube. The length of the transmitting fiber is 1500 mm.

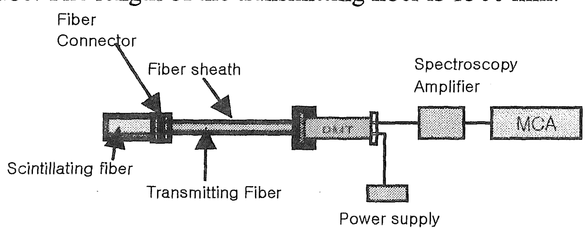

Fig. 1. Experimental setup used for the test of the optical sensors

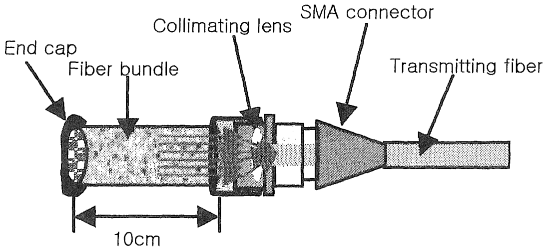

Fig. 2. Optical coupling between the sensor and the transmitting fiber

The other end of the transmitting fiber is fixed on the front window of a Hamamatsu PMT (type H5784) without any coupling medium. The H5784 is operated by a low-consumption high-voltage power supply and a low-noise preamplifier(Hamamatsu model C-7139). The electrical current from the photomultiplier tube is converted into a voltage pulse by the preamplifier, which is highly resistant to the noise. The PMT used has a broad spectral response between 300 and 650 nm with a peak sensitivity at 420 nm. The output signals from the preamplifier are then amplified by the spectroscopy amplifier (Canberra model 2012). Pulse-height spectra are obtained by feeding the output of the spectroscopy amplifier to the PC-based MCA (Ortec model trump 8k-32 and MAESTRO 32).

Table 1 The specification of plastic optical fiber

Core Refractive Index(n_1)	1.492
Clad Refractive Index(n_2)	1.402
Numerical Aperture(n_1^2-n_2^2)	0.51±0.33
Max Attenuation(dB/m)	0.19
Acceptance Angle(2sin^{-1}[N.A.])	61°
Operating Temperature (°C)	-55°C to +70°C
Minimum Radius of Bend (mm)	60

For each measurement, the radioactive liquid source contained in a vial was placed in close contact with the sensor as shown in **Fig. 3**. The source vial was plugged into a cylindrical lead shield with an opening at the bottom end. The end tip of the source protruded through the opening. The measured time is 5 minutes for all cases. To investigate the collimating effect of the lens, the same types of the sensor are used with and without the optical lens. Maximum signal outputs were obtained by carefully adjusting the position of the end tip of the transmitting fiber around the focal point of the lens.

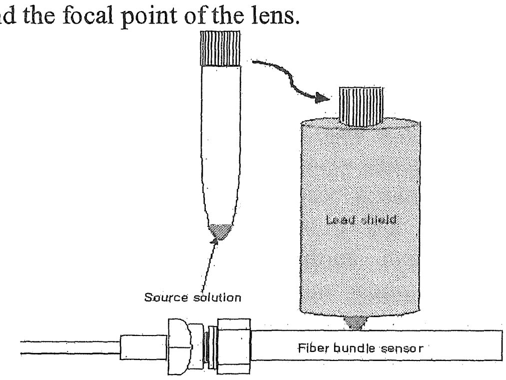

Fig. 3 Arrangement of the source and the fiber sensor for detection

To see the effect of the casing material for sensor, we made 3 types of the sensor with each having the same number of fibers (20 strands), but having 3 different casing materials: stainless steel, aluminum and PVC, respectively. The length of the sensors is 5mm and the thickness of the casing material was chosen to be 0.8 mm. These sensors were used to obtain the pulse-height spectra for a 3 μCi ^{137}Cs source. To investigate the effect of thickness of the casing material, we constructed sensors of aluminum case having 2 different thicknesses: 0.4 mm and 0.6 mm. These sensors were used to obtain the pulse-height spectra for the same source.

III. Experimental Results and Discussion

Figure 4. (a) and (b) show the pulse-height spectra obtained for a 3 μCi Cs-137 source with the sensors having different number of fibers. Case (a) is obtained with using the lens, and case (b) without the lens. The spectral value in each channel is the total count minus the background count. It is evident from the figures that using more fibers in the sensor increases the detection efficiency, which is indicated by higher spectral values. Also noted is that by using the lens, the spectra in the higher channels shrink to the lower channels while the spectral peaks, observed around channel 75, become a little higher. This feature is common for all types of the sensor. This implies that the lens retards a substantial portion of the lights generated in the sensor from entering the transmitting fiber, since a count in a higher channel results from a larger light output. This feature is further confirmed in **Fig. 5**, which shows the total count summed over all channels for each of the sensors. For every type of the sensor the total count obtained without the lens is almost twice the number obtained without the lens. The spectra, however, do not give any information about the energy of the incident gamma rays.

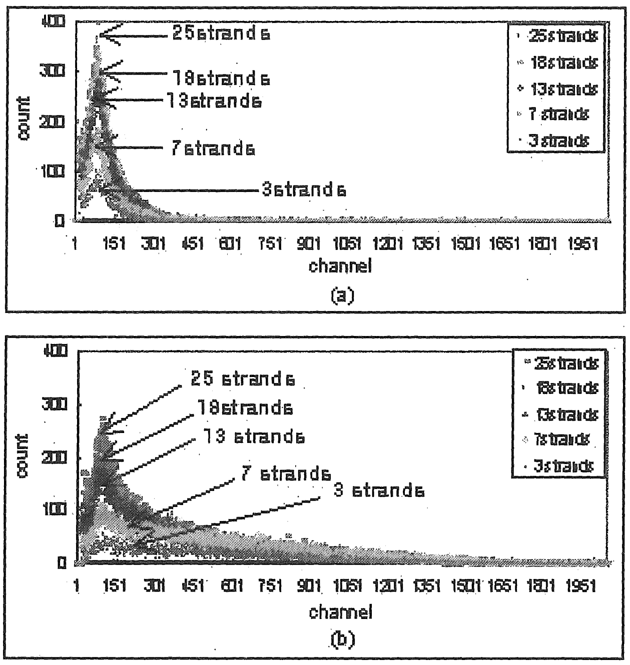

Fig. 4. Pulse-height spectrum measured with the sensors having the different number of strands for a 3μCi Cs-137 source. (a) is the case using the lens, and (b) is the case without using the lens. Measured time is five minutes for every case.

In order to check into the proportionality of the measured total count to the source activity, we tested the sensors having 3, 7, 15 strands with 3 relatively calibrated ^{137}Cs sources: 1.2 μCi, 1.6 μCi and 4.3 μCi contained in vials. The activities were relatively determined from the count rate of each vial by comparing with that of a 3 μCi source using an NaI(Tl) detector. The 3 μCi solution source had been prepared by pipetting a tiny amount from a known volume of 100 μCi. It was a best estimate value. We assume that the true activities of the sources used may be different from the relatively determined values they are proportional to the presumed values. Fig. 6 shows the measured total count versus the activity. It is clear from the figure that an excellent proportionality (less than 5 % discrepancy) exists for each of the sensors, although the proportionality constant is slightly different from sensor to sensor. This result demonstrates that it should be possible to develop reasonably sensitive gamma ray sensors even with a 3-strand fiber bundle.

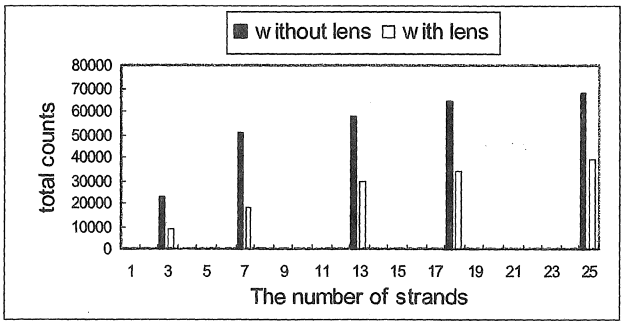

Fig. 5. The total counts measured with sensors having the different number of strands. 'unused' denotes the measurement using the lens. 'use' denotes the measurement without using the lens.

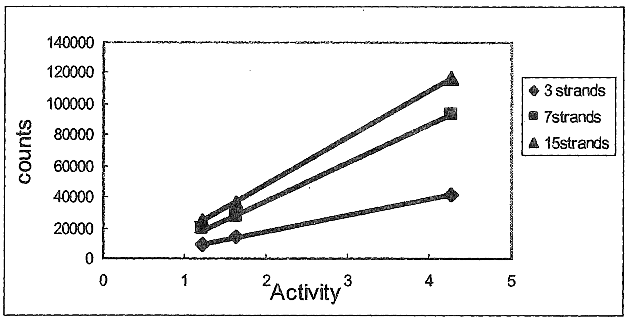

Fig. 6. Proportionality of the total count with the source activity measured with the sensors having 3, 7, 15 strands.

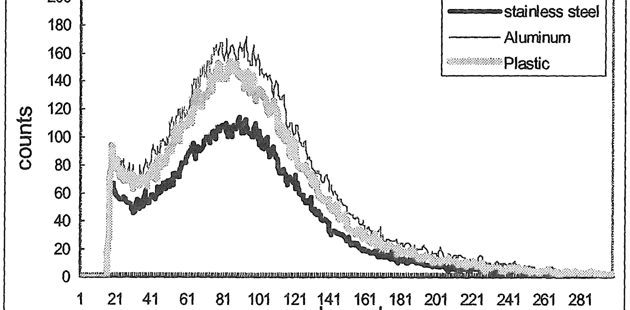

Fig. 7. Pulse-height spectra measured for a 3μCi Cs-137 source with sensors made of 20 strands of fibers with different tube materials

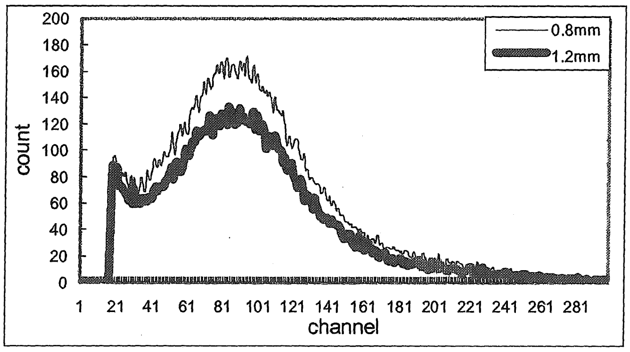

Fig. 8. Pulse-height spectra measured for a 3 μCi Cs-137 source with the sensors made of 20 strands of fibers in aluminum tubes of different thickness

Figure 7 shows the pulse height spectra measured with sensors having the same tube thickness but different tube materials. It is found that the detection efficiency is highest with the aluminum tube and lowest with the stainless steel tube, the efficiency of the plastic (PVC) tube being slightly lower than that of the aluminum tube. The efficiency of the stainless tube is about half the efficiency achieved with the aluminum tube.

Figure 8 shows the pulse height spectra measured with sensors of aluminum tubes having different thicknesses. It is found that the detection efficiency of the sensor with the tube of 0.8mm diameter is much higher than that of the 1.2 mm tube. Considering that the difference of the tube thickness is only 0.4 mm and the linear attenuation coefficient of aluminum is 0.197 cm^{-1}, this large difference of the detection efficiency cannot be explained by attenuation in the tube wall of the incident gamma rays. There should be some other factors such as interaction of the secondary electrons generated in the tube material, which also influence the detection efficiency. Since it is electrons rather than gamma rays that actually produce scintillation lights in the fiber, the secondary electrons generated in the tube wall may also significantly contribute to the generation of the scintillation lights. We can deduce from these results that the detection efficiency of the optical fiber sensor is sensitively affected by the casing material and thickness of the case.

IV Conclusions

The plastic scintillating fiber has been used to investigate the feasibility of using it for detection of gamma rays. Several types of sensors were constructed by packing different numbers of the fibers into aluminum, stainless steel and PVC tubes, and tested to detect the ^{137}Cs gamma rays. It is found that the sensors constructed with a few strands of the fibers in aluminum tubes are sensitive enough to be employed in μCi-level environments.

The use of an optical lens between the multi-fiber sensor and the transmitting fiber does not properly function for collimating the lights. It is also found that the thickness and type of material used for the sensor casing is important parameters affecting the detection efficiency. Our investigation suggests that plastic, aluminum or aluminum coated with plastic can be a desirable material for the casing material of gamma ray sensors.

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