PROGRESS IN THE DEVELOPMENT OF SCINTILLATING
OPTICAL FIBERS

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Starting with 1 inch diameter PVT scintillator as a preform, the authors have drawn fibers of several diameters ranging from 1 to 4 mm. These fibers have been coated in line with the draw to form optical fibers. Several cladding materials whose index of refraction ranges from 1.35 to 1.55 have been used. The most successful fiber has been obtained with an extra thick (200 micron) cladding of silicone in combination with a linear draw, as opposed to a spool draw. This fiber is acceptable, but it is extremely fragile and its quality is difficult to control. The authors are currently constructing a 12 channel hodoscope with 1 mm spatial resolution using 4 mm diameter fibers. An account is also given of the progress made in using the Avalanche Photo Diode (APD) operated in the Geiger mode as the photo detector.

Introduction

Starting from the 1977 summer workshop held at Brookhaven, the authors have been working on the development of a fine grained hodoscope for use in the very high rate environments which might be expected to prevail at a high luminosity accelerator. Earlier work on scintillating filaments¹ produced 1 mm diameter scintillators with a useful length of the order of 15 cm. In order to produce larger useful lengths it was decided to use the expertise of the fiber optics industry and to draw and coat scintillating optical fibers with a cladding of lower refractive index than that of the scintillator (about 1.6). Early results of this effort have been previously reported on^{2,3,4,5,6} and in the present report we summarize the successes and failures of this effort. We also report on the fabrication scheme currently employed to assemble a prototype hodoscope by coupling 4 mm diameter fibers to 11 mm diameter Photo Multiplier Tubes (PMT). We also present the progress made in coupling the fibers via a short tapered light guide to an Avalanche Photo Diode (APD) operated in the Geiger mode.

Fiber Development

The hodoscope element is a scintillating optical fiber produced by drawing a 1 inch diameter PVT scintillator preform, to a fiber which is clad in line with one of several optical cladding materials. The fiber so obtained is then evaluated in the laboratory by excitation with electrons from a Ru 106 source. The fiber is characterized as to yield in photoelectrons as measured using the RCA 8850 PMT and as to attenuation length. Several scintillators have been tried, and the best results have been obtained with BC434 supplied by BICRON.⁷ Three classes of cladding materials have been found to give relatively useful results. These are ultraviolet cured acrylic, heat cured silicone, and heat cured glass resin. Of these only the silicone and the glass-resin gave acceptable light yields. The best overall results have

been obtained using the silicone cladding. The glass resin, in the best cases, gave results almost as good as those of the silicone clad fiber, but the results varied by as much as a factor of 2 from one run to another. Consequently it has been decided to concentrate on the silicone clad, BC434 fiber.

The bond between the silicone cladding and the PVT cone is rather weak, and the resulting fiber deteriorates as a result of handling. We plan to explore the possibility of applying a buffer coat on top of the silicone cladding in order to improve its ability to be handled.

Two methods of applying tension to the fiber as it is drawn have been employed. In one case the fiber is wrapped around a capstan and then around a take-up reel which supplies the tension. In the other method the tension is applied via pinch-wheels, and the fibers are cut into canes of appropriate length as they are being drawn.

The disadvantage of the capstan method is that as the fibers are wound on the take-up reel, they acquire a permanent set corresponding to the radius of the wheel. For 1 mm diameter fibers this is no problem as they can easily be stretched straight after being cut to size. For larger diameters this is not practical and the pinch-wheel cane-draw method is used. The disadvantage here is that the pinch-wheel damages the silicone surface. To compensate for this the cladding is made extra thick - about 90 microns as opposed to about 10 microns.

Using the cane draw, the optical yields are generally worse than using the capstan draw. In all cases, the poor bonding results in poor quality control giving variations from run to run of the order of 40%.

For reasons having to do with diameter matching between fiber and PMT as well as due to economic considerations, we have recently pulled some 4 mm diameter fibers.

Typical results are summarized in the following table where all fibers are cane-drawn BC434 clad with heat cured silicone.

Diameter mm.	Yield at 50 cm photoelectrons	Attenuation length cm
1	4	100
2	8.6	110
4	16	120

It should be pointed out that we do not understand the short attenuation length for the 4 mm diameter fiber. Indeed the attenuation length should be about 250 cm according to a simple model we propose in

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Ref. 6. The anomalously low attenuation length may be due to a particularly poor surface contact between core and cladding in this particular case. In any case, from the point of view of light yield, the 4 mm fiber should give adequate light to build a prototype hodoscope which is virtually 100% efficient for fibers whose length is on the order of 50 cm.

Fig. 1. Hodoscope module assembly showing connections to PMT's at one end and tensioning screws at other end. Upper 6 fibers of a 12 fiber bilayer module are shown.

Construction of Hodoscope

A prototype hodoscope module has been constructed and is shown schematically in Fig. 1. The module consists of 2 layers of 6 fibers per layer with the fibers in the upper layer being laterally displaced by about one half diameter relative to those in the lower layer. The fibers are 4 mm in diameter. There is a gap of about 1 mm between adjacent fibers in a given layer. This is done so that the center to center distance between fibers can be accurately controlled despite variations in fiber diameter. The spatial resolution is such that a particle can be located as being in a 1.6 mm window depending upon which fiber or pair of fibers has been hit. This corresponds to an r.m.s. error of about 0.5 mm.

The ribbon formed by the layer of 6 fibers is about 30 mm in width. These fibers are then coupled to 6 Hamamatsu R1635 PMT's of diameter 9 mm by fanning up and down and left and right as shown in the figure. The important thing is that in the direction of the ribbon width, the PMT assembly also occupies about 30 mm, and so modules of 6 can be added in this direction to make the hodoscope as wide as required. At the other end the fiber is glued to a brass stud which can be tightened with a screw to apply the tension necessary to keep the fibers straight. The second layer of 6 fibers is dealt with in a similar way but with the locations of the PMT's and the tensioning screws being interchanged. A full fledged hodoscope can now be constructed by adding modules of 6 fibers in the direction of the width of the ribbon. Such a prototype has been assembled and checked in the lab, but has not yet been tested at the accelerator.

Avalanche Photo Diodes

Photodiodes small size and immunity to effects of magnetic fields make them ideal for readout of the scintillating fiber.

Three methods of coupling fibers to silicon photodiodes have been tried. The exit numerical aperture of a fiber is about 0.34 after one attenuation length. This corresponds to an exit half-cone of 20 degrees as shown in (a) of Figure 2. About 15 percent of the light was transferred here. The irregular surface of the standard window supplied on the to-18 package contributed to the losses.

Fig. 2. Three coupling schemes.

The lens-window for the package in (b) of Figure 2 enabled about 9 percent of the light to be transferred.

The glass cone in (c) of Figure 2 performed the best. It has a protective cladding. Here 40 percent of the light was transferred. The 2 mm scintillating fiber is coupled to the 2 mm cone with optical grease. The exit of the cone is cemented to the APD with "crazy glue".

When an RCA silicon APD is cooled to minimize dark current and biased beyond its breakdown voltage, incident light pulses trigger fast Geiger pulses. The Geiger mode is more sensitive than the linear mode. The RC recovery time of passive quenching with a resistor is about one microsecond. This imposes a corresponding rate limitation on one channel.

Photodiodes for these tests were purchased from RCA. Their entrance apertures are 1.3 mm. They were optimized for the Geiger mode. A half-megohm quench resistor is attached 2 cm from the anode inside the cold fixture where the temperature is maintained near minus 70 degrees Centigrade. The external load is a two kilo-ohm resistor. The positive bias voltage is applied to the cathode.

The external end of the fiber is coupled to a PMT. A small scintillation counter behind the fiber in coincidence with the PMT provides the trigger for penetration of the fiber by an electron from the Ruthenium source located outside the cold fixture 50 cm from the APD.

At the breakdown voltage of 368 volts the detection efficiency is zero as shown by the data plotted in Figure 3. As the voltage is increased to 400 volts the detection efficiency increases up to a maximum of about 80 percent. The stability of the setup was confirmed when the maximum efficiency was confirmed seven months later. The Ruthenium source was moved 15 cm closer to the fiber and the efficiency improved appropriately for an attenuation length of 1.5 meters. This efficiency is plotted as an open circle in Figure 3. No accidental triggers were

Fig. 3. APD detection efficiency for a 2 mm scintillating fiber excited by electrons from Ru^{106} .

identified. Accidentals to account for the 20 percent inefficiency are not possible.

The 80 percent maximum efficiency is consistent with the average number of PMT photoelectrons at 50 cm (8.6), the PMT quantum efficiency (0.17), the coupling efficiency (0.4), the APD quantum efficiency (1.4) and the APD triggering probability per photoelectron (0.2). If the number of photoelectrons were doubled, by use of an antireflection coating for the 440 nm scintillator peak for example, the limiting efficiency would become 96 percent.

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