Visible light photon counters as high quantum efficiency photodetectors and applications

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ABSTRACT

The Visible Light Photon Counters (VLPCs) have been developed as a result of the joint work between the UCLA and the Rockwell International Science Center since 1988. The VLPCs with quantum efficiencies approaching 80% and having avalanche gains of 30000, rate capabilities of 50 millions per second per millimeter square with a time resolution better than one nanosecond have been applied to High Energy Particle Physics Research, Medical Imaging and Particle Astrophysics. A survey of VLPC development with some results and applications will be presented.

INTRODUCTION

The VLPCs as photodetectors with high quantum efficiencies (70-80%) for 450-650 nanometer wavelengths, with high gains (around 3x10^4) and high speed (5x10^7 sec/mm^2) with a time resolution of better than a nanosecond, are filling an important gap that could not be filled with any other known photodetector. The efficient single photon detection capability makes the devices very unique. Since 1988 there have been many publications on this subject; therefore this is a good time to briefly review VPLC development and some of the results.

The VLPCs were developed jointly with the UCLA and Rockwell International Science Center using the grants from the Department of Energy (DOE) for doing research and development on scintillating fiber tracking for High Energy Particle Physics. Tracking with scintillating fibers is very attractive because of their very high rate of tracking capability and their excellent multitrack resolutions. At present, the D0 experiment at Fermilab is planning to use scintillating fiber tracking as the central tracking system and there is a good possibility that the CDF (Central Detector Facility) Experiment at Fermilab will also use such a system.

Another attractive feature of fiber tracking using the VLPC readout is that they are not affected by magnetic fields. In addition the VLPC system can be far out of an active tracking volume, making it easily reached for service by using clear optical fibers between the scintillating fibers and the VLPCs.

During the last couple of years working with the Medical Department of UCLA we have been using the VLPCs for medical imaging. This has been very successful and the results will be published soon.

One difficult factor in using the VLPCs as photodetectors is that they require cryogenic temperatures. We believe that this is not a big difficulty factor. We have demonstrated fairly easy solutions for this.

VLPC DEVELOPMENT

The VLPCs are the modified version of the Solid State Photomultipliers (SSPM). With the UCLA contract they were modified to reduce the Infrared (IR) sensitivity down to about 2% while keeping the quantum
efficiency of the VLPCs high (around 70-80%). This was done by adding an anti-reflective (AR) coating on the front surface, and by reducing the ohmic contact layer's resistance in order to improve the rise time of pulses. In order to accomplish these goals, the VPLC epitaxial layer structure was changed from that of the SSPM. The operational characteristics of the VPLCs are well explained in an earlier publication, therefore it will not be repeated here. To accomplish the above goals the VLPC wafers underwent several productions. The results of the steps are shown in Figure 1 together with some comparisons with the best available vacuum photomultipliers in quantum efficiencies as a function of the wavelengths. The Infrared (IR) sensitivity part is not shown in the figure because it is below a level of 2% in quantum efficiencies. In this figure, HISTE is an acronym for High Intensity Scintillating Fiber Tracking Experiment.

FIBER TRACKING EXPERIMENTS

Scintillating fiber tracking experiments were performed at UCLA to determine photoelectron yields and tracking efficiencies using 3HF doped polystyrene fibers. Good results were obtained with collimated Beta-particles and Cosmic-rays. These results were obtained using single clad (PMMA) and 1200ppm 3HF doped polystyrene scintillating fibers of 835 micron thickness. Figure 2 shows the experimental setup using Cosmic-rays. Four meters of scintillating fibers (835 micron thick) were coupled to 3 meters of clear optical fibers of the same diameter. Photoelectron yields as a function of the Cosmic-ray telescope position are indicated in Figure 3. The VLPCs are rightly called photon counters. Figure 4 shows that single and multiphoton-electrons are well resolved due to the fact that the gain dispersion in the avalanche formation is less than 30% for a single photon-electron. Each avalanche occupies less than 10 micron diameter of the VLPC for about one microsecond. Figure 5 shows few Cosmic-ray tracks with the number of photoelectrons in corresponding fiber for each event.

Later experiments done at UCLA showed that 1200 ppm doping of 3HF fiber of the length used was not optimal and that 1500 ppm doping would have given us appreciably more photons through the scintillating fiber. This result was obtained jointly with Drs. M. Mishina (FNAL/KEK) and J. Park (UCLA) in an unpublished report. The result with three different doping concentrations shows that photoelectron yield is increasing with the concentration, and that self absorption of photons becomes a major factor in reducing the photons as the length of the fibers increases (see Figure 6).

More recently Kuraray Co. produced multiclad fibers with the second clad being fluorinated polymer. Some tests carried out at Fermilab showed that the numerical aperture of the fiber was considerably larger than the fiber with the PMMA clad alone. 70% more photons were obtainable from the multiclad fiber. The results are shown in Figure 7.

VLPC CASSETTE AND CRYOGENICS

After some research and development work done jointly with Dr. Michael Petroff of Rockwell International Science Center, we have found a relatively simple cryogenic cassette construction for keeping the VLPCs around the nominal temperature of 7K. The cassette with the OFHC (Oxygen Free High Conductivity) copper housing is shown in Figure 8. The VLPCs are cooled with the cold liquid helium gas. Part of the boil-off gas goes through the cassette to cool the VLPCs, ribbon cables and the optical fibers. The thin wall 304 stainless steel conducts very little heat because the enthalpy of the cold gas is fully utilized. An OFHC copper cold shield which is kept partly in liquid helium provides stable low temperature around the cassette. Each cassette is made for 32 channels of VLPCs. This figure also shows the Fermilab QPA02 amplifier cards. A six cassette system for a total of 192 channels of VLPC-fiber arrangement is shown in Figure 9.
**D0 COSMIC-RAY TESTS**

The D0 experiment is planning to put together a central tracking system having scintillating fibers with the VLPC readout. For this, a 3000 channel system was built to do tests with Cosmic-rays. Figure 10 shows the layout. The test results show that an average number of 11 and 20 photoelectrons were detectable from the singlet and doublet fibers (Figure 11). The results in the photoelectron yield agrees with the earlier UCLA Cosmic-ray results if we consider multiclad fibers. A tracking resolution of 127 microns was obtained that is close to what is expected from approximately a 735 micron core of scintillating fibers.

**OTHER APPLICATIONS**

The Physics and Radiology Departments of UCLA have been working jointly on Medical Imaging using scintillating crystals and/or scintillating fibers. The results have been very successful and there will be a publication on the subject soon.

The VLPCs may also be used as photodetectors for a fast ring imaging Cherenkov counter in fixed target experiments. In this the Cherenkov photons are focused by spherical mirrors into optical fibers that carry the photons onto the VLPCs.

**REFERENCES**

(2) M. Atac et al., Nucl. Instr. and Meth. A314, pg. 56, (1992)
(6) A.Bross et al., Contribution to this Symposium.
(7) D.M.Kaplan et al., Nucl. Instr. and Meth. A343, pg. 316, (1994)
FIGURE 1
Quantum efficiencies of the VLPCs as they were developed. It also shows the quantum efficiencies of vacuum photomultipliers in comparison.

FIGURE 2
Experimental arrangement for the Cosmic-ray tests.
Triggered by 1st & 4th Layers
with single p.e

Av p.e in Layer 2 with Mir □
Av p.e in Layer 2 No Mir +
Av p.e in Layer 3 with Mir ×
Av p.e in Layer 3 No Mir ◦

FIGURE 3
Photoelectron yield from 0.785 mm core of PTP/3HF doped polystyrene scintillating fibers as a function of the Cosmic-ray track position.

FIGURE 4
An impressive spectrum showing the photon counting capability of a VLDPC up to 10 simultaneous photons. The multiple peaks are discernible.
Very clean, typical Cosmic-ray tracks with the number of photoelectrons indicated. There was no detectable cross-talk between the channels.
FIGURE 6
Photoelectron yields as a function of the doping concentration of 3HF in polystyrene. Self-absorption becomes a major factor as the fiber length is increased.
Relative photon yield from the multiclaid and standard PTP/HF fibers of Kuraray Co. as a function of the position where the photons were produced.
FIGURE 8
A photograph of a 32 channel VLPC cassette. The penny in the picture shows the compactness of the unit.

FIGURE 9
A photograph of a 6 cassette arrangement in a liquid helium dewar. A total number of 192 channel VLPCs is used with this arrangement.
Scintillating Fiber Tracker

Single Element:

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<tr>
<th>2.4 m scintillating fiber</th>
<th>8.5 m clear (undoped) fiber</th>
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<tr>
<td>835 micron</td>
<td>965 micron</td>
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Mirror

Ribbon:

835 micron fiber with 870 micron spacing 1 X 128

FIGURE 10
The layout of the D0 Cosmic-ray experiment.
FIGURES 11 A&B
Average photoelectron yields from a singlet and the doublet of 3HF multiclad scintillating fibers.