Fast analog signal transmission for an air Čerenkov photomultiplier camera using optical fibers

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Abstract

A system to demonstrate fast analog signal transmission through optical fibers is presented. The dynamic range of output voltages is $2\ \mathrm{mV}$ to $1.0\ \mathrm{V}$ at a bandwidth of $150\ \mathrm{MHz}$. The intended future application is to transmit nanosecond photomultiplier pulses over distances of 150 meters with minimal pulse shape distortions. The advantages, problems and the further development potential are discussed.

Key words: Imaging Čerenkov telescope, analog signal transmission, Vertical Cavity Surface Emitting Laser diode (VCSEL), graded index multi-mode fiber.

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1 Introduction

The performance of the next generation imaging Čerenkov telescopes such as MAGIC [1] or VERITAS [2] depends on the quality of transmission of analog signals over a distance of up to 150 meters. Both telescopes will use photomultipliers as Čerenkov camera light detectors. The photomultiplier pulses with rise times as fast as 1.2 ns and pulse widths as short as 3 ns must be transmitted from the telescope camera to the central data acquisition electronics building with *neglible pulse dispersion, low noise,* and *minimal attenuation*. Fiber optic cables can offer this performance but also have significant practical advantages over low loss, high bandwidth coaxial cables. Their *low weight* and hence *low moment of inertia* put less strain on the telescope mount. Many fibers are packaged in a single cable of *low diameter* which is easier to install through the telescope mount. There is *zero cross talk* between cables and *no electromagnetic interference*. Metal free cables also protect the readout electronics from *lightning strikes* near the telescope. The alternative, to install the readout and the digitizing electronics in the telescope camera, introduces new problems such as weight and temperature control. Because of necessary

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design compromises such a system will be less flexible and of lower performance then electronics located in a data acquisition building.

The AMANDA experiment at the South Pole [3] has used a system based on analog pulses transmitted along fiber with an LED. In our system, a Vertical Cavity Surface Emitting Laser (VCSEL) is used to give a wider dynamic range at high bandwidth.

2 Transmitter and receiver

In order to demonstrate that fiber links can replace coaxial cable in an existing Čerenkov telescope the specifications for the system were as follows.

- A bandwidth of $140\ \mathrm{MHz}$ corresponding to a $2.5\ \mathrm{ns}$ rise time is required to accurately transmit the $7\ \mathrm{ns}$ wide signal pulses.
- The product of cable attenuation and amplifier gain should give a gain of 5 to match that of the current coaxial cable and amplifier system in the Whipple 10 m telescope [4].
- The range of output voltages from $2\ \mathrm{mV}$ to $1.0\ \mathrm{V}$ is designed to match the linear range of the LeCroy model 2249A 10 bit charge integrating ADC used in the present Čerenkov telescope.
- The fiber link voltage noise should be small compared to the combined effect of the night sky light background noise and of the shot noise of the photomultiplier tube. The combined noise has a minimum value in the order of 1 mV during Čerenkov light observations.
- The system should be linear to within 10% over the whole dynamic range.
- The power consumption per transmitter should not exceed 500 mW in order to keep cooling requirements to a minimum.
- Finally, the cost per channel must be comparable to 53 m co-axial cable plus a commercial amplifier. The total component cost per fiber link including 53 m of multi-mode graded index fiber should therefore be close to $200.

Figure 1 shows a simplified circuit diagram for the fiber link. To achieve the wide dynamic range a VCSEL is used in the transmitter. VCSELs can give a pulsed light output coupled into 62.5/125 micron fiber of 2 mW for a 20 mA pulsed drive current. A constant current source gives a bias current of 5-6 mA, well above the laser threshold of 3.5 mA. After a first stage voltage limiting amplifier a maximum signal current of 15 mA is generated by the OPA660 operational transconductance amplifier. The receiver converts the current signal from the photodiode with responsivity of $0.45\mathrm{A/W}$ into a signal of around 0.1 Volt which is fed into a final stage amplifier. The OPA620 was chosen as transimpedance amplifier because of its low current noise.

3 Measurements and results

Figure 2 shows the output pulse amplitude as a function of the input pulse amplitude. The plot shows good linearity from $2\ \mathrm{mV}$ to $1.0\ \mathrm{V}$. Hence the dy-

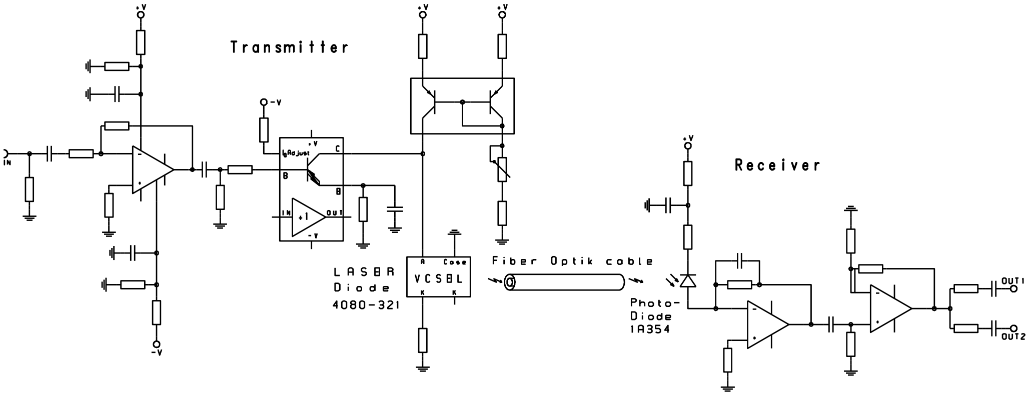

Fig. 1. Simplified circuit diagram.

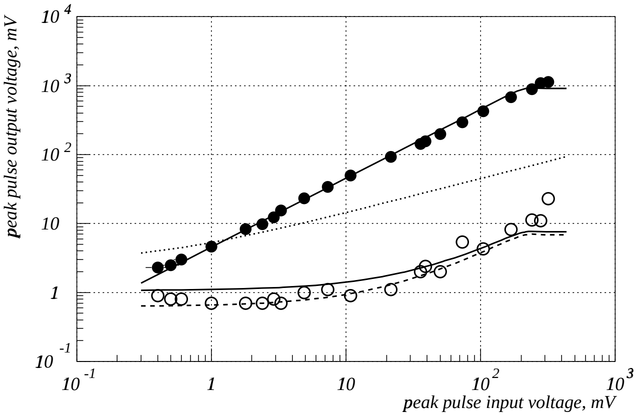

Fig. 2. Output voltage as function of input voltage. Filled circles: measured output signal. Open circles: measured noise. Solid lines: prediction for output signal and noise. Broken line: contribution of laser relative intensity noise. Dotted line: calculated inherent signal noise due to night sky background and photomultiplier shot noise.

namic range is better than 500. Saturation is caused by the limit on the transmitter amplifier. The response differs from a perfect linear behavior in voltage by less than 10 % and in the measured pulse charge by less than 10 %.

The root-mean-square fluctuation of the peak pulse height of 7 ns wide pulse measured at 400 MHz bandwidth is used as a measure of the link voltage noise. This is also shown in Figure 2. The measured values are in good agreement with those calculated [5]. For large signals the signal to noise ratio is better than 35 dB. This is determined entirely by the relative intensity noise of the VCSEL. As the laser diode is always biased above threshold, the relative intensity noise still dominates over thermal and amplifier noise even for very small signal pulse amplitudes. Over the whole amplitude range, the measured noise is smaller than $1/5$ of the inherent voltage noise of the input signal. The inherent voltage noise shown in figure 2 is the result of the photomultiplier shot noise and the night sky background noise.

Figure 3 shows the -3 dB bandwidth to be $150\ \mathrm{MHz}$. The bandwidth is deter-

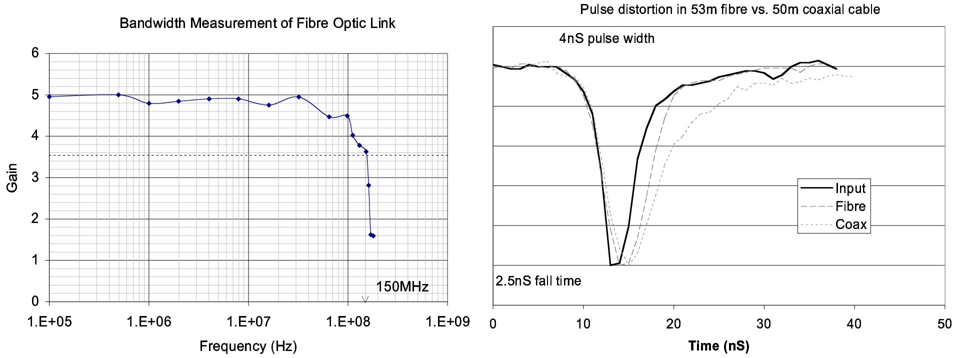

Fig. 3. Left: Frequency response. Right: Examples of pulse shapes.

mined by the value of the feedback capacitor and the resistor in the receiver transimpedance amplifier. Values are chosen to give stable voltage gain with the required bandwidth.

The VCSEL threshold current and the light output power per current are temperature sensitive. However we find that the link gain only changes by a maximum of 3 percent over a temperature range from 0° to $+30^\circ C$ of the transmitter and the cable. The VCSEL threshold current only changed by 0.6 mA over the same temperature range.

Figure 3 shows a 4 ns pulse after transmission over the fiber link and over 50 m of coaxial cable normalized to the same amplitude. The pulse dispersion in the coaxial cable is much greater than in the fiber. With co-axial cable the pulse width increases significantly and the amplitude was attenuated by 50 %. In the telescope system, maintaining a narrow pulse width allows the integration time to be shortened. This reduces the background noise of the pulse charge measurement.

During November 1998, two single channel fiber optic links were installed into the HEGRA CT1 telescope at the La Palma observatory. Plastic conduit was used to protect them and they have now worked without any problems for eleven months. Another prototype was installed into the Whipple 10 m telescope. In this case an indoor fiber optic cable was installed without any protection. The fiber was later accidentally damaged during work on other cables.

4 Future prospects

The combined bandwidth of the VCSEL, the multi-mode fiber and the photodiode exceeds 1 GHz for distances of 150 m. The *bandwidth* of the present prototype of $150\ \mathrm{MHz}$ is limited by the operational amplifiers used. Discrete transistor circuits are being investigated. These are low cost and have a low *power consumption* of 50 mW per channel. New low noise and high bandwidth operational amplifiers can give a link bandwidth of $350\ \mathrm{MHz}$. Since MAGIC and VERITAS aim to digitize the pulse shapes at a maximum rate of 500 Mega samples per second, this is sufficient.

The *dynamic range* of the current system is 500. We have learned from the VCSEL manufacturer, Honeywell, that for low duty cycles and short pulses the laser current and therefore the optical output power of the laser can be increased ten-fold. Therefore, it is theoretically possible to get a dynamic range of up to 10^4. To match this performance dual range input circuits to extend the input voltage range of 500 MHz 8-bit FADC circuits are being developed by both MAGIC and VERITAS.

We have not yet tested fiber optic cables for damage caused by slow but continuous *bending and torosion* in a telescope moving around two axis. However, since the fibers are flexible while the jacket of the cable contains a material such as Kevlar to take up the mechanical stress we expected suitably designed fiber optical cables to have better bending and torosion properties than coaxial cable.

The cost of components per channel to build a 120 channel system for the Whipple telescope system including 100 m of fiber optic cable is $200. This is mainly concentrated in a few components: the fiber, the laser diode, the optical connectors, the photodiode, and the operational amplifiers. Placing multiple VCSELs or photodiodes on a single chip array and connecting to fiber via a MT connector can reduce costs of these components. Discrete transistor solutions are considerably cheaper than operational amplifiers.

A drawback of VCSEL is that they are class 3b lasers which require *laser safety* precautions. Transmitter and the receiver must be enclosed with additional safety interlock mechanisms to avoid accidentally exposure to IR radiation. A further safety measure are connectors with shutters that block the beam when opened.

5 Conclusions

We have demonstrated that analog photomultiplier signals can be transmitted by optical fibers using VCSELs as light sources giving a performance suitable for imaging Čerenkov cameras. Analog signal transmission over optical fibers can be used for next generation telescopes such as MAGIC or VERITAS.

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