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A 100 MHz FIBER OPTIC SINGLE TRANSIENT GAMMA RAY DETECTION SYSTEM

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Abstract

A fiber optic system has been developed to measure single transient gamma rays. The gamma ray signature is converted to light by the Cerenkov process in a 20 cm length of radiation resistant optical fiber. The signal is transmitted over 1 km of optical fiber and detected by state-of-the-art, 175 MHz analog receivers.

The receivers are based on silicon PIN detectors with transimpedance hybrid amplifiers and two stages of power amplification. The dc coupled receivers have less than 2% distortion up to 5 volts with less than 10 mV rms noise and a responsivity of 37,500 V/watt at 800 nm.

A calibration system measures relative fiber to fiber transit time delays and "system" sensitivity. System bandwidth measurements utilized an electron linear accelerator (Linac) with a 50 ps electron pulse as the Cerenkov light source.

The system will be described with supporting calibration and characterization data of parts of the system and the whole system.

Introduction

Methods of detecting and recording fast (1 GHz) single transient gamma ray signals using fiber optics have been reported in past conferences.^{1,2,3,4} For gamma diagnostics that are slower (50 MHz) and smaller flux levels, another fiber optic system has been developed. The system is based on the Cerenkov process for the radiation-to-light converter. The receivers were developed for maximum linearity, gain and dynamic range. A calibration system was designed to measure relative timing between fiber optic channels and to monitor system integrity. This paper will describe the system and concentrate on the receiver parameters, the system characteristics, and the time calibration system.

System description

The basic system consists of a line-of-sight (LOS) from the radiation source, a polyethylene gamma to electron converter, plastic-clad-silica (PCS) radiation resistant fiber for the transducer, 1 km of continuously gas blocked fiber optic cable, a narrow band filter, fused biconical taper star couplers, receivers and oscilloscopes. This system configuration is shown in Fig. 1.

Fig. 1. System schematic.

The LOS collimates the radiation and provides a localized high flux region for the radiation-to-light converter. Approximately 20 cm of PCS fiber are placed along the top side of a polyethylene helix in the LOS. The polyethylene has a relatively high radiation-to-electron-to-Cerenkov light conversion efficiency⁵ for gamma rays.

The fiber on the helix is at a 45° angle to the gamma rays to maximize the Cerenkov coupling efficiency and minimize the time smearing. The time smear is 89 psec per vertical inch of exposed fiber. Relatively short lengths of PCS fiber are used to get away from the intense radiation environment. The 125 μ m core ITT PCS fiber is coupled by ITT connectors

to 1 km of Corning SDF fibers (140 $\mu\text{m}/100 \mu\text{m}$). The SDF fiber was specified to have greater than 300 MHz-km response at 850 nm and 1300 nm. Its measured NA through 1 km of cable is 0.25.

The light was coupled through the filter assembly by microscope objectives mounted on translation mounts. The lowest insertion loss was 1.8 db. The star couplers were specified to have a 10:1 splitting ratio. In some channels the star couplers were cascaded to increase the dynamic range. There are mode selection problems associated with cascading star couplers that will be discussed later. The filtered light from a star coupler was detected by a receiver which drives one high bandwidth oscilloscope.

Optical receiver

Each optical receiver contains a thick film hybrid preamplifier, intermediate amplifier, and power amplifier. The photodetector is a five millimeter square area silicon pin diode. The diode is mounted in the hybrid along with two bipolar silicon microwave transistors as shown in Fig. 2. The preamplifier is a current shunt feedback arrangement having a responsivity of 700 V/W. The output of the preamplifier is applied to the input of two Comlinear Corporation video amplifiers that develop an additional voltage gain of 55. Table 1 details the receiver specifications.

Fig. 2. Hybrid transimpedance amplifier with silicon PIN.

Table 1. Receiver Characteristics

1. Bandwidth	DC to 175 MHz
2. Overshoot	< 5%
3. Responsivity	37,500 V/W at 800 nm
4. Noise equivalent power	1 μW
5. 2nd Harmonic Distortion for 5 V PP output	< -40 dBc

The optical detectors have DC response to simplify calibration of the system. To reduce offset drift, each hybrid is mounted on a thermoelectric block with a substrate mounted temperature sensor that holds the preamplifier at a constant temperature, ten degrees below ambient. The temperature feedback arrangement holds drift to a $\pm 40 \text{ mV}$ limit.

Eighteen optical detectors were fabricated. Three detectors were mounted in each rack mountable unit. Table 2 indicates their bandwidth variations. The bandwidth variations are due to construction tolerances in the thick film hybrid circuit.

Table 2. Bandwidth of Detectors

Unit No.	Channel No.	BW (MHz)
1	1	175
	2	185
	3	200
2	1	195
	2	180
	3	215
3	1	205
	2	182
	3	190
4	1	196
	2	180
	3	190
5	1	217
	2	186
	3	209
6	1	200
	2	187
	3	188

Time calibration system design

The time calibration sources were remotely located as shown in Fig. 3. Two optical transmitters were placed downhole. The philosophy followed was to use broadband sources and narrow band filters to eliminate channel to channel differences in material dispersion.

Fig. 3. Schematic of remote time calibration sources and distribution scheme.

The air spark gap was a commercially available fast risetime, broadband source purchased from Xenon Corp. Its pulse characteristics are shown in Figs. 4a and 4b. Although the broadband peak amplitude was significant, several factors reduced it to marginal levels. Only a small slice of the broadband spectrum was used, due to the use of narrow band filters at 900 nm and only one leg of an 8 x 8 star coupler was used to couple energy into the fiber system. These losses provided 100 mV to 150 mV signals which were only a few times noise. The recording system is illustrated by Fig. 5. Signal averaging with a Tektronix 7912AD increased the signal to noise ratio.

Fig. 4a. Spectral characteristics of air spark gap.

Fig. 4b. Pulse shape of air spark gap.

Fig. 5. Schematic of recording system set up for time calibrations.

In the field setup, a two fiber bundle received light from the air spark gap. One fiber was the leg of the 8 x 8 star which coupled to the 6 data channels. The other fiber from the bundle bypassed the PCS, and connected directly to the SDF to provide a reference pretrigger for timing measurements.

The 900 nm laser diode was a backup in case the air spark gap failed. Its fiber pigtail was coupled directly to one leg of the 8 x 8 star to provide pulses for all 6 data channels. This backup light source proved to be most useful, not only as a timing backup, but also for performing relative sensitivity measurements. It proved to be the only source with enough intensity to provide light through all 6 primary channels as well as 9 secondary, less sensitive, channels. Therefore, relative sensitivity of all channels could be compared. The laser diode waveform through the system is shown in Fig. 6. After recording all channels on the 7912AD with a constant reference trigger, relative timing differences can be calculated. Repeatability measurements on one channel using the air spark gap source indicate a standard deviation of 0.37 nanoseconds. Table III compares the timing data from the air spark gap and the laser for several calibrations. It is evident that both systems give essentially the same results.

Fig. 6. Laser diode pulse through the system.

Table 3. Cross Channel Timing

DATA CHANNEL	FILTER ($\Delta\lambda$)	LASER DIODE			AIR SPARK GAP		$\overline{\Delta T}$	σ (NS)
		28 FEB 1984	28 FEB 1984	29 FEB 1984	28 FEB 1984	29 FEB 1984		
		ΔT (NS)	ΔT (NS)	ΔT (NS)	ΔT (NS)	ΔT (NS)		
1	(40 nm)	14.3	13.5	14.5	24.7*	13.2 13.7	13.8	.5
2	(10 nm)	30.0	30.6	30.2	30.3	29.3	30.1	.5
3	(40 nm)	0	0	0	0	0		
4	(10 nm)	11.8	10.8	11.8	12.2	10.8	11.5	.6
5	(40 nm)	4.7	5.2	4.4	5.2	3.9	4.7	.6
6	(10 nm)	7.8	8.5	8.2	7.9	6.4	7.8	.8

*Not used to calculate average ΔT

System parameters

This section will discuss the matching of system bandwidths, the channel to channel sensitivities and the star coupler splitting ratios.

The bandwidth of each fiber channel was measured using Cerenkov radiation produced by the EG&G/Santa Barbara Operations LINAC. It was assumed that all the receivers would have a nominal 175 MHz bandwidth that would have a minimal effect on the system bandwidth, which would be limited more by the material dispersion in the fiber and the amount of time smear caused by the fiber in the radiation beam (20 cm). Therefore, all fibers were measured with the same detector and two different interference filters.

Figure 7a is a typical impulse response, Fig. 7b is the corresponding frequency response from six fiber channels using the Linac and 900/40 nm filter. All channels are 65 MHz $\pm$ 5 MHz at the f3db point. Figures 8a and 8b shows the impulse response and the frequency response for the same fibers and detector but using a 900/10 nm filter. The narrower filter has increased the bandwidth to 85 MHz $\pm$ 10 MHz.

Fig. 7a. Typical impulse response. The signal was filtered with a 900/40 nm interference filter.

Fig. 7b. Frequency response of six fibers using a 900/40 nm interference filter.

Fig. 8a. Typical impulse response. The signal was filtered with a 900/10 nm interference filter.

Fig. 8b. Frequency response of six fibers using a 900/10 nm interference filter.

System sensitivity

The spectral region of peak sensitivity was determined by measuring the system sensitivity as a function of wavelength using the Linac. The Linac produces a 50 ps burst of electrons that, when incident on fibers, will produce a 50 ps burst of Cerenkov light. Cerenkov light is broadband with a λ^{-3} dependence. Therefore, its impulse response will be smeared by material dispersion if it is transmitted through 1 km of fiber and detected by the receiver of interest. The result, Fig. 9, is a plot of intensity vs. time (wavelength) which has built into it Cerenkov production, fiber attenuation and detector sensitivity. Repeating the measurement with a narrow band filter will identify a time for that wavelength. The peak sensitivity for this system was at 900 nm.

Fig. 9. Cerenkov spectrum thru 1 km of fiber as detected by a silicon receiver.

To obtain a radiometric calibration, a monitored d.c. Xenon light source was used. Energy was coupled into the system at the downhole star coupler. The power was measured coming out of the PCS fiber during installation. The power level was then measured at the detector and the associated receiver d.c. voltage shift. From these measurements one derives a system sensitivity of $1.1 \times 10^{-3} \text{ V}/\mu\text{W} \pm 0.5 \times 10^{-3} \text{ V}/\mu\text{W}$ where the voltage is measured out of the receiver and the power is coupled into a 125 μm core, ITT PCS fiber terminated with ITT Canon connectors.

Cascading star couplers

To increase the dynamic range of one fiber channel, fused biconical taper couplers were used with a nominal 10:1 split between the two legs. In some channels these were cascaded to obtain nominal 100:10:1 splits. Modal selection in this type of star coupler prevents this type of performance.

A nominal 10:1 splitting ratio depends on the launch conditions into the star. For a "uniform" distribution input, the high output leg carries the low order modes, appearing like a bright circle in the far field, and the low output leg has the high order modes, appearing like a doughnut in the far field. If the low output leg (high order modes) is coupled to a similar star coupler, the split ratio decreases because mainly high order modes are excited. Table 4 illustrates what is expected as split ratios from measuring each star separately, and what was measured as a cascaded system.

Table 4. Cascaded Star Coupler Losses Normalized to the Lowest Loss Channel

Channel	Predicted Loss (db)			Measured Loss (db)		
	Low	Medium	High	Low	Medium	High
1	1	-9.83	-19.8	1	-11	-16
2	1	-9.4	-17.3	1	-12	-15.3
3	2	-9.6	-17.08	1	-11.8	-13.8

From Table 4 it is evident that if splitters are to be used in a predictable cascaded geometry, then splitters that are not modal selective must be used.

Conclusion

A multichannel single transient 85 MHz analog recording system has been developed along with a time calibration system. The system has 1% linearity up to 5 V out of the receiver with a 40 db dynamic range. The relative channel to channel timing accuracy was ± 0.6 ns. With a 10 nm filter the channels had an 85 MHz ± 10 MHz bandwidth matching, and 65 MHz ± 5 MHz with a 40 nm filter. It has also been shown that modal selective star couplers cannot be used in a predictable manner when there is selective modal excitation.

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