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A high-bandwidth multichannel fiber optic system for measuring gamma rays*

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Abstract

We describe an analog fiber optic gamma-ray diagnostic system that can transmit signals through fiber cables 600 to 700 m long with a system bandwidth exceeding 1 GHz and measure the relative timing between signals to within 0.3 ns. Gamma rays are converted to visible light via the Cerenkov process in a short length of a radiation-resistant optical fiber. A graded-index optical fiber transmits this pulse to a recording station where the broadened pulse is compensated for material dispersion and recorded using a streak camera. The streak camera can simultaneously record 20 to 30 data channels on a single piece of film. The system has been calibrated using electron linear accelerators and fielded on two experiments.

Introduction

We have developed an analog fiber optic diagnostic system for measuring gamma rays produced by underground nuclear explosions. Our goals in designing this system were to faithfully transmit and record analog signals of about 1 GHz through fibers up to 1 km long and to measure the relative timing between signals to within 0.3 ns. To accomplish these goals, we had to overcome the harsh conditions encountered during the fielding of a nuclear test: an intense radiation environment (which darkens glass fibers in a nonlinear fashion), physical difficulties (abrasion, strain, and breakage of cables), temperatures up to 45°C, and long transmission distances.

In our system, a collimated beam of gamma rays impinges on a material that converts some of the gamma rays to high-energy electrons by Compton scattering. An optical fiber of radiation-resistant glass intercepts some of these Compton electrons to produce Cerenkov light. The light pulse travels through a graded-index optical fiber cable to the ground surface, where it is recorded using a spectral equalizer and a streak camera.

Although the idea of converting gamma radiation to Cerenkov light using an optical fiber placed in the gamma-ray beam has been with us for almost ten years,[1] optical fiber technology has only recently advanced to the point that allows exploitation of this idea to its full potential. To date, several versions of this diagnostic system have been developed and used on nuclear tests.[2,3] These earlier systems recorded the signals using photomultipliers and high-bandwidth oscilloscopes. Our system records the signals using a streak camera.

A fiber optic/streak camera system provides several advantages over a conventional coaxial cable/oscilloscope system:

- The system can transmit and record frequency components up to about 1.5 GHz through a 1-km-long fiber. This is important because the gamma-ray signals produced by nuclear explosions may have frequency components greater than 1 GHz. Furthermore, if the frequency response of the system is known, even higher-frequency components can be recovered by using mathematical deconvolution. In comparison, a conventional coaxial cable system using a 1-km-long cable is limited to about 400 MHz.

- The system can handle multiple channels. Hence, this system can replace six high-speed photomultiplier tubes and about 30 oscilloscopes. Such a reduction in recording hardware provides several benefits: the streak camera requires less space in the recording trailer and is easier to install and maintain. Furthermore, using one fiber-optic detector/recorder system in place of several coaxial cable systems allows more accurate comparison of the relative amplitudes and timing of signals from different channels.

- The system is not susceptible to electromagnetic interference since the data are transmitted as light pulses rather than electrical pulses. The system is also immune to moisture-caused problems that plague coaxial systems.

In addition, the system is simple, dependable, and able to function in a harsh environment. Underground nuclear tests are conducted at the bottom of deep holes (200 to 600 m deep and 2 to 3 m in diameter) or in deep horizontal tunnels. In a "down-hole shot," the nuclear device is mounted in a cylindrical device canister. Diagnostics, consisting of detectors at the ends of collimated lines of sight that view the device, are installed in a diagnostics canister mounted above the device canister. Coaxial and fiber optic cables connect the detectors to recording trailers located at the ground surface. After the device and diagnostic canisters and the attached cables have been lowered to the bottom of the hole, the hole is filled with sand, gravel, and epoxy plugs to prevent radioactive gases generated by the blast from reaching the ground surface. Of course, no access is possible once the canisters have been lowered. The canisters and cables must be designed to withstand the abrasion and impact of sand, gravel, and rocks plummeting several hundred metres down the hole, temperatures up to 110°F, and moisture. When the device is detonated several days later, the diagnostic must survive an onslaught of intense radiation, record the desired data, and transmit it "uphole" to the recording system before it is destroyed.

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System description

The fiber optic diagnostic system consists of a detector, a high-bandwidth optical fiber, a spectral-streak equalizer, and a streak camera recording system (Fig. 1a).

Detector

The detector is located at the end of a collimated line of sight that views the nuclear device. It consists of two converters—one that converts gamma rays to Compton electrons and one that converts these electrons to Cerenkov light. The first converter consists of a slab of low-Z material, e.g., beryllium and polyethylene. The second converter consists of a radiation-resistant fiber of pure silica running along the rear of the first converter.

The detector operates as follows: a fraction of the gamma radiation impinging on the slab is converted to high-energy Compton electrons that are predominantly forward scattered through a 2 to 5-cm section of the glass fiber. Electrons that traverse the fiber faster than the velocity of light in the glass generate Cerenkov light. (For pure silica having an index of refraction of about 1.5, electron energies must exceed 174 keV to produce light.) Cerenkov light is highly directional for a well collimated electron beam. To achieve maximum coupling of the Cerenkov light into the fiber and to maintain good time response, the slab and fiber must be aligned at a 45° angle with respect to the gamma-ray beam (Fig. 1b).[4,5]

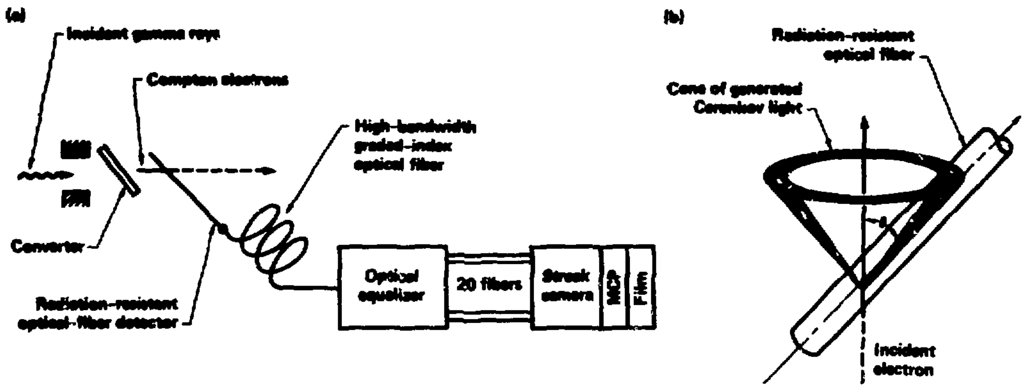

Figure 1. (a) The fiber optic diagnostic system, consisting of a detector, a high-bandwidth optical fiber, a spectral-streak equalizer, and a streak camera recording system. Gamma rays from a nuclear source are converted into high-energy Compton electrons that generate light in a radiation-resistant optical fiber. The light is transmitted through a long graded-index fiber to the spectral-streak equalizer, which processes the light for recording by the streak camera. (b) The cone of Cerenkov light generated when Compton electrons traverse the fiber faster than the velocity of light in the fiber. To transmit the maximum amount of light up the fiber, the angle θ must be about 45°.

Unfortunately, radiation darkens the glass fibers used as Cerenkov converters by dislodging electrons and possibly atoms. To avoid attenuation caused by this radiation darkening, we have used the most radiation-resistant fibers available: plastic-clad silica (supplied by ITT) and fluorosilicate-clad silica (supplied by Raychem).[6,7] Because this type of fiber has a very poor bandwidth, however, we must keep it as short as possible (3–4 m) and make a transition to high-bandwidth graded-index fiber for the link uphole.

To reduce radiation darkening further, we used a low-Z material as the gamma ray-to-Compton electon converter instead of brass, which was used previously. This substitution increased the effective yield of Cerenkov light by 30%.[4]

Studies have also shown that radiation-induced darkening can be lessened by maintaining the fiber at an elevated temperature.[8] The degree of darkening diminishes over time as the dislodged electrons migrate back to their positions, and this process ("thermal bleaching") accelerates as temperature increases. Although this effect is small during a brief pulse, it can be important when the same fiber transmits additional pulses a few tens or hundreds of nanoseconds later. When necessary, the detectors have been heated to take advantage of this effect.

Despite these precautions, radiation-induced darkening of the fibers attenuates the light signal nonlinearly. This severely limits the upper end of the dynamic range of an individual detector. Hence, the transient induced absorption of the fiber must be known to determine the linearity of the detector.[7]

Optical fibers

Signals from the converter fiber are transmitted uphole by a graded-index optical fiber cable having a numerical aperture (NA) of about 0.2. The fiber has a 50-µm-diameter core and can transmit 1.3-GHz signals (at 800 nm). The transition from the large-core high-NA plastic-clad silica or fluorosilicate-clad converter fiber to the small-core lower-NA transmission fiber is inefficient, resulting in a 12 to 17-dB loss of signal intensity, respectively. In addition, the transition from plastic-clad silica fiber was very difficult to make.

Spectral equalizer

A sharp pulse of light transmitted by an optical fiber broadens for two reasons: modal dispersion, which occurs because the path lengths of individual light rays are slightly different, and material dispersion, which occurs because different wavelengths of light travel at different velocities.

The spectrum of the generated Cerenkov light is spectrally broad, and its energy distribution follows a $1/\lambda^3$ dependence on wavelength. Because of material dispersion, the initially temporally sharp pulse of multicolored light broadens when transmitted over the length of fibers that we use (600–700 m). For the region of the spectrum in which we operate (780 to 820 nm), the material dispersion ranges from about 133 to 107 ps/nm·km.

Pulse broadening limits the amount of information that can be transmitted. Although we cannot correct for peak broadening caused by modal dispersion, we can compensate for broadening caused by material dispersion either 1) by limiting the observed portion of the spectrum to a wavelength range of ≤2 nm or 2) by using optical equalization.

The first method uses a narrow-band interference filter to select ≤2-nm portions of the spectrum. Although this method effectively limits the spectral width, it does so at the expense of signal amplitude in a system that already suffers from low signal levels resulting from the inefficient processes of Compton and Cerenkov conversion.

The second method overcomes this problem by taking a larger (40-nm) spectral "bite" of the optical signal, thus gathering more light. A 40-nm portion of the spectrally wide signal is extracted and compressed as follows. (In this explanation, we trace the path of a signal produced by the source at a given instant in time.) Light from the fiber is focused onto a reflection grating that disperses the light into its spectral components. The spectrum is focused onto a linear fiber array arranged so that each fiber catches a different 2-nm band of the spectrum and cut to different lengths so that (early) longer-wavelength light pulses travel farther than the (late) shorter-wavelength pulses (Fig. 2).

The relative lengths of the fibers can be adjusted according to the requirements of the recording system. If a photomultiplier tube is used, the fiber lengths are cut so that all signals arrive simultaneously. If a streak camera is used, the lengths are cut to reduce the arrival-times difference between the long- and short-wavelength pulses. The signals arrive one after the other and are superimposed by the streak camera.

Streak camera

The streak camera reassembles the selected 40-nm portion of the dispersed spectrum as follows: the fiber array is aligned parallel to the sweep direction of the camera (Fig. 2). Light from the fibers is imaged on the camera's photocathode and generates electrons. Sweep plates in the camera deflect the stream of electrons across the output phosphor to which the film is exposed. If no deflection voltage were applied to the sweep plates, the electrons generated at the photocathode would be focused on the output phosphor in the same pattern as the fiber array. With the constantly increasing sweep voltage applied, however, the electrons corresponding to each fiber can be made to strike the same point on the phosphor. That is, because the sweep voltage increases with time, electrons generated by shorter-wavelength light (which arrives last) see a stronger deflection field than electrons generated by longer-wavelength light (which arrives first). When the camera's sweep speed is carefully coordinated with the speed of signals through the fibers in the array, the camera superimposes the signals at the same point on the phosphor.

As explained above, this path is taken by a signal generated at one instant in time at the source. A complete signal appears as a streak on the film. To convert the streak to an intensity-vs-time curve, the film is read using a microdensitometer, and the data are processed by computer.

By selecting only a narrow 2-nm band of wavelengths, each fiber in the array provides an output signal that is a more faithful representation of the input signal from the downhole light source, but its intensity is weak. However, the streak equalization technique combines the outputs of all 20 fibers on the same spot of the streak camera's phosphor.

This equalization could also be achieved by using a fiber array alone if a photomultiplier recording system is used[9] or by using a streak camera and very carefully matching its sweep speed to the grating.[10] By combining these techniques,[11] however, we increase the operating flexibility 1) by making the sweep speed independent of the optical characteristics of the grating, 2) by eliminating the need to place the grating very close to the camera, and 3) by providing a means, by adjusting the lengths of the fiber in the array, of fine-tuning the system. The added complexity of the equalizer array is more than offset by greater operating flexibility.

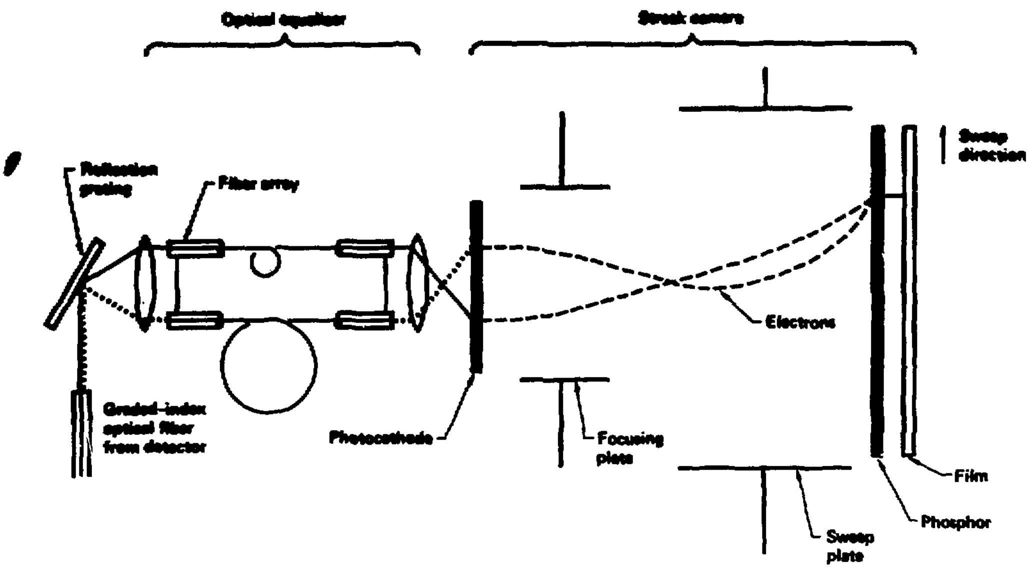

Figure 2. Operation of the spectral-streak equalizer and streak camera recording system. Light from the fiber is focused onto a reflection grating (lens not shown) that disperses the light into its spectral components. The spectrum is focused onto a linear array of 20 fibers arranged so that each fiber catches a different adjacent 2-nm band of the spectrum. The fiber lengths have been adjusted to reduce the arrival-times difference between the long- and short-wavelength pulses. Thus, the faster lower-frequency light pulses (solid line) travel farther than slower higher-frequency pulses (dotted line). The signals arrive one after the other at the end of the fiber array where they are focused onto the camera's photocathode and generate electrons. Sweep plates, to which a constantly increasing sweep voltage is applied, however, deflect the electrons so that they strike the same point on the phosphor. The phosphor emits light that is recorded on the film.

We built our streak cameras using streak tubes manufactured by RCA, 40-mm microchannel plate intensifiers from ITT, and camera electronics and housings made at LLNL. We selected the streak tubes that had the best photocathode efficiency in the region of 780–820 nm. Signals are recorded on Kodak Royal-X pan film. To date, we have used two different sweep speeds—60 ns and 15 ns.

We believe that our present streak camera system offers several advantages over high-speed photomultiplier tubes and oscilloscopes. It can record signals having risetimes of about 100 ps. It can accept many channels. Although the preceding explanation describes the process of recording data from a single channel, we have typically used streak cameras to record 25 channels of information simultaneously (Fig. 3). Because the data are recorded by one camera on the same piece of film, interchannel timing and relative amplitude can be more precisely determined. It can replace up to 40 oscilloscopes, which allows corresponding reductions in costs.

Calibration

The process of lowering the device- and diagnostic-canister assembly downhole and filling the hole plus the high downhole temperatures can significantly alter the fiber lengths, and thus fiber transit times, by cable stretching and thermal expansion.[12] Because analysis of the data from a nuclear test requires precise knowledge of the transit time from each detector relative to all other detectors, we designed a calibration (or "dry run") system to establish the transit time from each detector after the canister assembly has been emplaced downhole. This calibration system also measures transmission losses resulting from fiber hookups and checks the system's integrity.

In a typical calibration, a pulse is sent downhole to trigger a laser diode that produces a narrow (<120 ps risetime) 500-mW optical pulses. This pulse is split, injected into the "unused" ends of different converter fibers, transmitted to the streak camera, and recorded on film. Analysis of the film indicates the relative transit time from each detector to the recording system.

System performance

The time response of the system was measured using linear accelerators at EG&G (Goleta, CA) and Argonne National Laboratory (Chicago, IL). Figure 4a shows the signal obtained when a 25-nC pulse of about 0.025 ns FWHM was injected into a 9-m-long optical

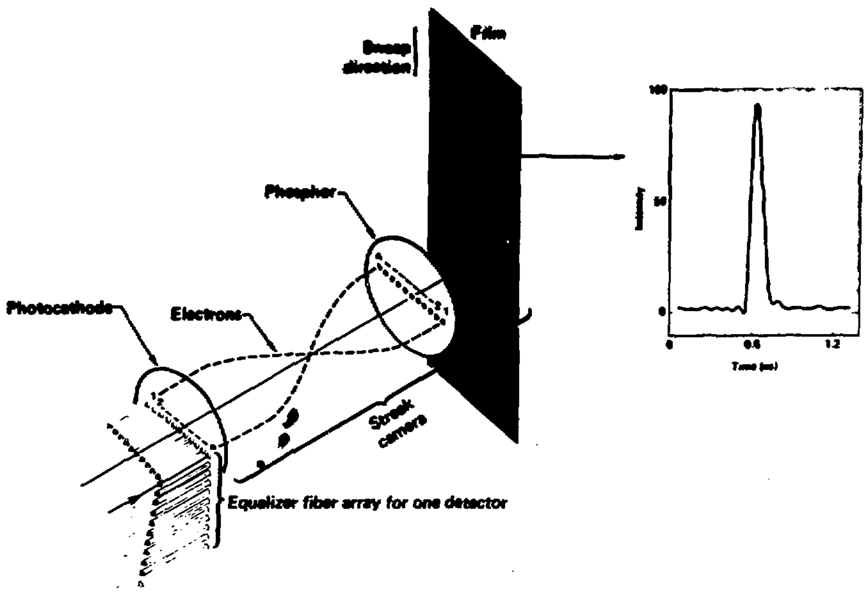

Figure 3. Configuration of a streak camera system that can record multiple optical fiber channels. The vertical fiber arrays of the optical equalizer for each channel are positioned in front of the photocathode. As the electrons move toward the phosphor, they are not only deflected vertically by sweep plates (not shown) but also focused onto the phosphor, which is intensified to expose the film. A complete signal appears as a streak on the film. The film is read using a microdensitometer, and the data are processed by computer to produce an intensity-vs-time curve.

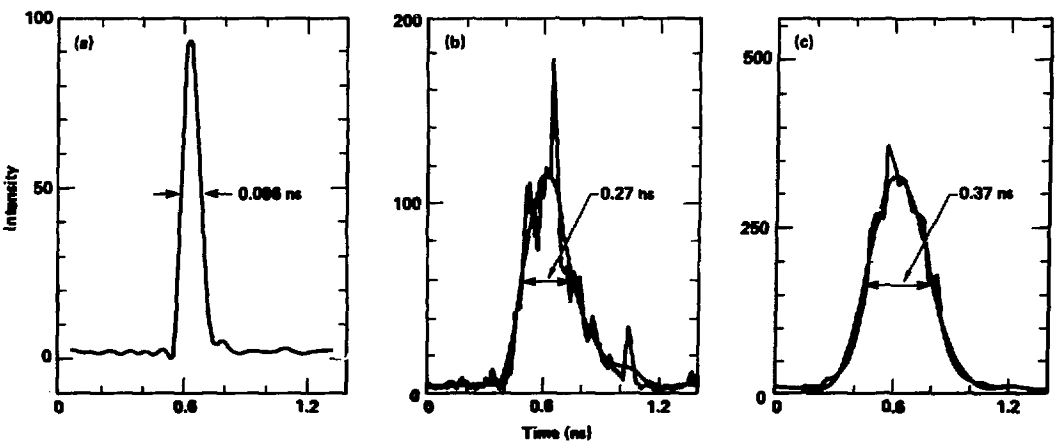

Figure 4. Time response of the system measured using a 25-nC pulse of about 0.025 ns FWHM produced by a linear accelerator. (a) Signal obtained when the pulse was injected into a 9-m-long optical fiber and recorded by the streak camera using a 15-ns sweep time. (b) The 0.27-ns FWHM signal obtained when the pulse was transmitted through the entire system (detector, 600-m transmission fiber, equalizer, and streak camera) using a 15-ns sweep length and (c) the 0.37-ns FWHM peak obtained using a 60-ns sweep.

fiber and recorded by the streak camera using a 15-ns sweep time. Figures 4b and 4c show the results when this pulse was transmitted through the entire system (detector, 600-m transmission fiber, equalizer, and streak camera); the pulse was recorded as a 0.27-ns FWHM peak using a 15-ns sweep length (Fig. 4b) and a 0.37-ns FWHM peak using a 60-ns sweep (Fig. 4c).

At the same time, we tested the equalizer to determine that the lengths of the fibers had been adjusted correctly. By rotating the output end of the fiber array 90° with respect to the sweep direction, we obtained a signal oriented at a 45° angle with respect to the sweep direction (Fig. 5). This indicated that the pulses in the individual fibers were properly spaced in time.

We have fielded this fiber optic diagnostic system on two nuclear events and have obtained excellent data on a total of 55 channels.

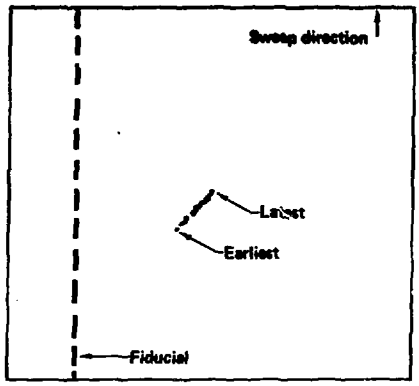

Figure 5. Relative arrival times of light pulses at the output end of the optical equalizer fiber array. The signal oriented at a 45° angle with respect to the sweep direction was obtained by rotating the fiber array 90° with respect to the sweep direction. The signal shown here indicates that the pulses in the individual fibers were properly spaced in time.

Projected improvements

We foresee significant improvements in the accuracy, sensitivity, and dynamic range of this system when certain technological advances are achieved. Two of these improvements would extend the lower limit of the system:

- A streak camera having increased quantum efficiency (QE). The QE of the present system is 0.2% at 800 nm. An increase to 3–4% would give a ten-fold increase in sensitivity.

- A high-bandwidth graded-index fiber having a larger-diameter core (up to 100 μm). Such a fiber would reduce the mismatch at the junction with the radiation-resistant convert fiber and thus decrease the signal loss at this junction.

A third improvement would extend the upper limit of the system:

- A glass fiber having increased resistance to radiation-induced darkening. Such a fiber would allow observation of more intense beams. The development of better converter materials and changes in the detector geometry are being investigated.[4]

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