TITLE: RADIATION-INDUCED IMAGING SYSTEM OVER LONG FIBER-OPTIC BUNDLES

AUTHOR(S): James W. Ogle, Douglas Thayer, Larry D. Looney, P-14

Frank Cverna, George Yates, P-15

Charles E. Iverson, Steven S. Lutz, Melvin A. Nelson, EGG/SB0

Bruce Whitcomb, EGG/LVO

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Radiation-induced imaging system over long fiber-optic bundles

James W. Ogle, Douglas Thayer, Larry D. Looney, Frank Cverna, and George Yates

Los Alamos National Laboratory, Physics Division
Post Office Box 1663, MS D410, Los Alamos, New Mexico 87545

Charles E. Iverson, Steven S. Lutz, and Melvin A. Nelson

EG&G, Inc.
Post Office Box 98
Goleta, California 93117

Bruce Whitcomb

EG&G, Inc.
Post Office Box 1912
Las Vegas, Nevada 89101

Abstract

Scintillator, fiber, and detector technologies have progressed over the last few years so that it is now possible to record radiation images over optical fiber bundles 1 km in length. Scintillators that emit at 730 nm will be coupled with wavelength-multiplexing techniques to telecommunication fibers for transmission to a demultiplexer and detection by GaAs microchannel-plate image-intensifier tubes. The technique and design considerations, such as time-integrated versus time-resolved images, resolution and system dynamic range will be described.

Introduction

In the field of prompt plasma diagnostics, remote image detection using fiber-optic bundles offers several advantages over the conventional practice of putting detectors and TV systems near the site of radiation-image formation and reading the data out remotely.^{1,2} Fiber systems may be smaller and more flexible than their electrical counterparts and, at the same time, provide higher bandwidth, faster readout, immunity to electromagnetic interference, and perhaps most importantly, the possibility of a totally passive input system, requiring no electrical components. Moreover, electronic instrumentation at the output end of fiber bundles can be operated in a controlled environment where it is accessible for last-minute checks and adjustments, and the high cost of equipment can be amortized over repeated use.

A fiber system to acquire radiation images is usefully divided into three parts: the radiation-to-light converter or scintillator; the transmission medium or fiber bundle (including input and output optics); and the detector (image intensifier, streak camera or vidicon). Since each of these three parts has a response which varies with wavelength, optimum system sensitivity results from selection of components which have relatively well-matched spectral responses.

Component Selection

The spectral transmission of fibers is examined first because it is not generally variable in commercial fibers. Consequently, other system parameters are varied to fit the fiber response. Typically, fibers have attenuation curves such as that shown in Figure 1. This curve demonstrates that fibers transmit red light better than blue and that light sources and detectors should be sought with emission or sensitivity in the red portion of the spectrum. Corning short-distance fiber (with core/cladding sizes of 100 μm /140 μm) was selected for the present system because of its good transmission properties and as a tradeoff between spatial resolution and sensitivity.

Figure 1. Spectral attenuation of typical FO-5 cable.

Many scintillators have been developed for fiber radiation-measurement applications.¹⁻³ The curves in Figure 2 show the spectral efficiency of a broad range of such scintillators. The spectral efficiency is defined as the ratio of light energy emitted (in a 1-nm-wide spectral band) to the amount of energy deposited in the scintillator by radiation. Table 1 shows several important scintillator characteristics, including a number of time-response parameters, peak emission wavelength, and overall efficiency (integrated over time and wavelength). Selection of the best scintillator for a particular application depends on the system constraints. Blue scintillators, for example, tend to be more efficient and have faster time response. Red scintillators, however, may provide larger signals when transmitted over long lengths of fibers. The recently developed L-735 was chosen for the present system because of its strong red emission.

Figure 2. Calibrated emission spectra of experimental scintillators.

Table 1. Scintillator Characteristics

Scintillator	RI*	FWHM*	DECAY*	IRI*	%/NS*	%*	LAMBDA*
	NS	NS	NS	NS			NM
BC-422	0.24	1.58	1.72	4.44	0.90	1.91	390
BHTP	0.18	0.45	0.40	1.26	0.38	0.24	355
Liquid A	0.23	1.20	0.90	3.23	0.55	0.84	460
L650A	0.21	1.65	1.52	3.53	0.06	0.13	650
SR640	2.66	14.45	12.09	26.30	0.02	0.27	640
L735	0.21	1.54	1.27	2.77	0.06	0.10	735
L841	0.52	1.88	1.37	3.99	0.02	0.04	850

*RI = time-response risetime

FWHM = time-response full width at half maximum amplitude

DECAY = time-response decay time

IRI = risetime of time-response integral

%/NS = rate of energy conversion at time-response peak

% = total energy converted (integrated over time and wavelength)

LAMBDA = peak emission wavelength

Several materials are available for image-intensifier photocathodes, and the spectral sensitivities of these materials vary widely. The curves illustrated in Figure 3 show the response of several common photocathode materials. The curve for GaAs shows the greatest sensitivity in the red and near-infrared region of the spectrum and, consequently, an image intensifier with a GaAs photocathode was chosen for the present system.

Coherent fiber bundles provide one fiber per pixel and are the most direct method of using fibers in imaging. Commercial fiber bundles certainly offer impressive resolution and sensitivity for short-distance applications. In lengths of many tens or hundreds of meter, however, coherent fiber bundles become prohibitively cumbersome and expensive.

When sufficient light is available, wavelength-multiplexing techniques can be employed to decrease both system size and cost by transmitting on a relatively small number of fibers the large amount of information contained in an image.^{6, 7} Wavelength multiplexing increases the bandwidth of optical fibers by color-coding information at the system input (multiplexer), transmitting all data channels in parallel, and decoding the information at the output (demultiplexer). A wavelength multiplexer and a demultiplexer were designed and incorporated into the present system.

Figure 3. Spectral sensitivity of several photocathode materials.

Wavelength-Multiplexing Technique

The operation of the wavelength multiplexer and demultiplexer is illustrated by reference to the spectrograph depicted in Figure 4. Assuming white light is emitted by the fiber on the left, the first lens collimates the white light, the prism disperses the light into its spectral components, and the final lens focuses each spectral component into an image of the fiber core which is slightly displaced from its neighbors, resulting in the familiar spectral line. This is the demultiplexer.

Figure 4. Fiber optic wavelength multiplexer/demultiplexer.

Fortunately, the light path in such a system is reversible. Thus, if the image plane of Figure 4 is illuminated with the full spectrum, the fiber will accept blue light from the top edge and red light from the bottom, with the intermediate colors falling in between. So, the multiplexer is just the demultiplexer in reverse.

Since a single fiber receives and transmits the image information contained in a single line across the object, stacking fibers into a linear array allows acquisition of the two-dimensional image as a series of parallel spectrally-coded lines.

Multiplexer Design

The system spectrum (product of scintillator efficiency curve, fiber transmission curve and detector sensitivity curve) extends at its half-maximum height from about 690 nm to 810 nm. The source image for the multiplexer covers a rectangular area measuring about 1.8 mm by 3.4 mm. The long dimension is acquired by stacking 24 fibers into a linear array on 0.140 mm centers. Since the spatial resolution of the multiplexer is approximately the diameter of the fiber core, 0.100 mm, there are 18 resolution elements or pixels across the dispersion dimension of the image, giving an average spectral resolution of 6.7 nm/pixel. Assuming use of a 50 mm lens, this is equivalent to an average angular dispersion of about 0.917 degrees/nm.

The required dispersion is small enough that it can be supplied by either a prism or a diffraction grating. A suitable diffraction grating would have about 100 g/mm. Unfortunately, such a low-frequency grating produces many diffraction orders and has low efficiency. A prism, however, has only a single order and is highly efficient. In fact, previous experiences has shown the prism system to be at least 6 times more efficient than the grating system. The three-element direct-vision prism depicted in Figure 4 is convenient because the light is dispersed without appreciable deviation, thus simplifying optical alignment.

System Sensitivity

A schematic diagram of the present system is shown in Figure 5. Radiation is imaged on the L-735 scintillator at the left. This image is relayed via an optical transfer system to a coherent fiber bundle for a time-resolved measurement. The fiber bundle face is highly mirrored (except for the widely-spaced fibers). Consequently, the image reflects from the fiber bundle face to the 10% beam splitter and into the wavelength multiplexer. Twenty-four Corning short-distance fibers, 800 m long, connect the multiplexer to the demultiplexer. The demultiplexer output is imaged on the GaAs microchannel plate image intensifier. The time-integrated intensifier image is recorded on a vidicon.

Figure 5. Remote radiation image recording system using long fiber optic bundles.

A calculation of system sensitivity was performed based on the following formula:

$$S = \left(\frac{E}{E_p} \right) \left(\frac{e\%/nm}{100} \right) \left(\frac{SA}{4\pi} \right) (\Delta\lambda)(T)(e_{opt}) \quad (1)$$

where S = sensitivity in photons per rad

E = energy deposited in scintillator per rad

e%/nm = % efficiency/nm of scintillator in converting rads to light

SA = solid angle subtended by lens as seen by scintillator

$\Delta\lambda$ = spectral width used (in nm)

T = fiber transmission at filtered wavelength

e_{opt} = efficiency of optical system (lenses, prisms, and beamsplitters)

E_p = photon energy at filtered wavelength

This relation reduces to:

$$S = (10^6)(T)(e\%/nm)(\Delta\lambda)(\lambda)(PF)(T)(e_{opt})(NA \cdot D)^2 \quad (2)$$

where t = fluor thickness in cm

λ = wavelength in nm

PF = NA profile factor

NA = system numerical aperture

D = fiber core diameter in cm

Using $t=2$ cm, the product of $e\lambda/nm$ and $\Delta\lambda$ (690 nm to 810 nm) equals 0.08, $\lambda=750$ nm, $PF=0.5$, $NA=0.20$, $D=0.01$ cm, $T=0.4$, and $C_{opt}=0.05$ (10% beamsplitter and 50% lens system transmission at 750 nm), the formula predicts a sensitivity of 480 photons/rad out of the fiber. Experiment has shown this value to be slightly conservative. Assuming a radiation field of 3500 rads and depositing the photons uniformly onto a photocathode area equal to a single spectral line, 0.18 cm $\times$ 0.01 cm, gives an energy density of about 2.5×10^{-3} ergs/cm². Because of the weighting of the spectrum, however, the sensitivity is more nearly 4×10^{-3} ergs/cm² at the center and about half that at the edges. The dynamic range of the present system is expected to be about 100:1. Moreover, if the 10% beamsplitter were not necessary for the present system, the sensitivity might be great enough to consider making time-resolved image measurements on a streak camera, depending on the time response required.

Conclusion

In summary, by taking advantage of the recent development of red scintillators such as U735 and red-sensitive GaAs photodetectors, and applying efficient wavelength-multiplexing techniques, it is now feasible to record time-integrated radiation images over optical fiber bundles 1 km in length. This has three direct benefits: one, active components can be operated in a controlled environment; two, sophisticated and complex instrumentation is accessible for last-minute checks and adjustments, and three, systems costs can be reduced by repeated use of expensive equipment.

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Appendix

Chemical names and sources for the scintillators of Table 1:

BC-422 is commercially available from Bioron, 12345 Kinsman Road, Newbury, Ohio 44065.

BHP is 0.14M 4-bromo-4'-(5-hexadecyl)-p-terphenyl dissolved in Pseudocumene.

U735A is 8 g/l 2-phenyl-5-(4-biphenyl)-1,3,4-oxadiazole plus 8 g/l 1,1,4,4-tetraphenylbutadiene dissolved in Pseudocumene.

U650A is 0.03M DCM* plus 0.1M Coumarin-480* in Benzyl Alcohol.

SR640 is 0.002M Sulforhodamine-640* plus 0.02M Coumarin-540A* in Benzyl Alcohol.

U735 is 0.02M UDS-722* plus 0.1M Coumarin-540A* in Benzonitrile.

U841 is 0.005M UDS-821* plus 0.1M Rhodamine-610-Perchlorate* in Benzyl Alcohol.

*Chemicals marked by an asterisk are laser dyes from Exciton Chemical Co., Inc., P. O. Box 51126, Overlook Station, Dayton, Ohio 45431.