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TITLE: SIGNAL ENHANCEMENT BY SPECTRAL EQUALIZATION OF HIGH-FREQUENCY
BROADBAND SIGNALS TRANSMITTED THROUGH OPTICAL FIBERS

MASTER

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Signal enhancement by spectral equalization of high-frequency broadband signals transmitted through optical fibers*

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Abstract

A new technique is discussed for signal strength enhancement of high-frequency (>1 GHz), spectrally-broad, analog signals through 1 km of optical fiber. The conventional method for optical measurement of high-frequency gamma ray signals is to use an optical fiber placed in the gamma radiation beam as a Cerenkov transducer. The radiation-induced optical signal is degraded by material dispersion in transmission through the fiber. To reconstruct the signal (which is carried by each wavelength) and preserve the high-frequency components, a narrow-band filter selects an appropriate bandwidth (1 nm). The filtered signal is detected using a high-speed, microchannel-plate (MCP) photomultiplier detector and recorded on high-speed oscilloscopes.

This new technique replaces the narrow-band filter with a wavelength multiplexer device. The broadband signal input is dispersed by a grating, and narrow spectral components are collected into an array of fibers used as optical delay lines to compensate for the material dispersion in the kilometer of fiber. The delay fibers, each cut to an appropriate length, couple the spectrally equalized light onto the detector. This technique improves the frequency response by eliminating the wing contributions of narrow-band filters, and increases the signal magnitude by utilizing more of the available broadband spectrum. The new technique is applicable to any optical system wherein material dispersion limits system bandwidth.

Introduction

The use and benefits of fiber optics for transmission of high-frequency analog transient phenomena have been reported before.^{1,2} Our ability to take advantage of the frequency response of high-grade, commercially available, single-window graded index fibers operated at the optimum designed wavelength is limited by material dispersion. Thus, in the optimum wavelength region, the narrower the spectral width of the signal the higher the frequency response of the system.³

A spectral equalizer (SPEQ) device has been developed⁴ that retains the frequency response of a narrow spectral width (<1 nm) while collecting light from a relatively large spectral band. This is achieved by canceling the effect of material dispersion over a limited (50 nm) spectral region. In this paper we will give a brief review of the spectral equalization concept, discuss design considerations, and report experimental verification of improved efficiency.

Concept and design of spectral equalization

A spectrally broadband impulse of light is temporally broadened by material dispersion when transmitted through a length of optical fiber.⁵ The resulting detected signal will be characterized by the spectral attenuation of the fiber and the spectral response of the detector. An example of this is shown in Fig. 1, the result of a 50 ps FWHM, 6 MeV electron pulse traversing an optical fiber and producing light by the Cerenkov process⁶ with a dependence on wavelength of λ^{-3} . The resulting 50 ps light impulse is dispersed by transmission through 1 km of optical fiber to a signal lasting more than 100 ns. When fiber absorption is considered, along with the response of the extended S-20 or GaAs MCP photomultiplier cathode surfaces, the peak signal amplitude is at 800 nm. To prevent the system response from being dominated by material dispersion, the pulse broadening contribution should be considerably less than the detector response (200 ps FWHM).⁷ This limits the acceptable detectable spectral width to ≤ 1 nm at 800 nm and eliminates the use of most of the available light.⁸

The SPEQ utilizes more of the available light. To accomplish this the high-frequency temporally dispersed broadband spectrum is inserted into a spectrograph. The spatially separated wavelengths are collected by a horizontal array of "equalizing" fibers. Each

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† At 800 nm, material dispersion in 1 km of fiber is 110-120 ps/nm.

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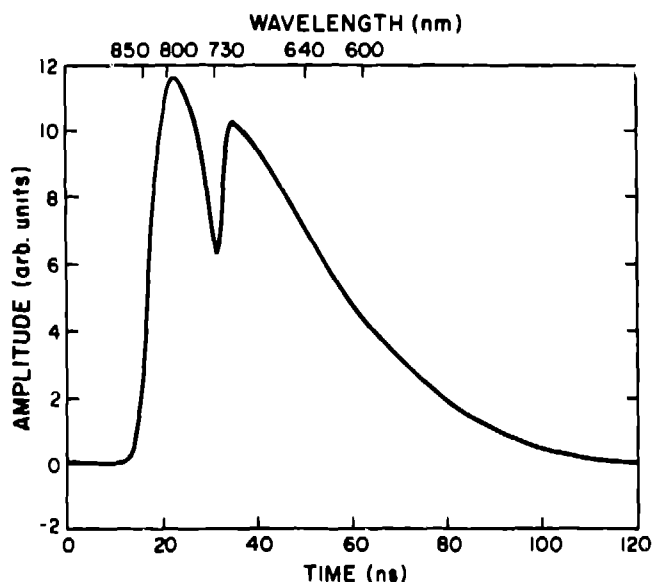


Fig. 1. Broadband Cerenkov spectrum created by a 50 ps electron pulse, transmitted through 1 km of optical fiber and detected by an extended S-20 MCP photomultiplier tube.

equalizing fiber is a delay line. It is cut in length relative to the rest to adjust for the material dispersion in the original fiber. All signals exiting the equalizing fibers will then be in temporal coincidence with each other. All signals are incident on the same photodetector (Fig. 2). The resulting increased photodetector signal, relative to that using the single-filter approach, is a function of the spectrograph efficiency and the number of fibers used.

The spectrograph (Fig. 3) consists of a horizontal array of fibers (Fig. 4) consisting of 2 graded index fibers identical to the long signal fiber and 34 equalizing Corning-type SDF fibers with 100 μm core and 140 μm clad diameter. A two-element collimating lens, whose parameters are tabulated in Table 1, is located on, and perpendicular to, the optical axis of the graded index fibers. A diffraction grating is located in the Littrow geometry on the opposite side of the lens from the fiber array. Light from a graded index fiber is collimated by the lens, diffracted by the grating and refocused on the horizontal fiber array by the lens, producing a spectrally dispersed signal across the fiber array. Each fiber accepts a 0.86 nm spectral width. Each fiber is cut to a different length in order to compensate for different arrival times and thus phase shift each wavelength to bring them all into coincidence. The equalized signals from all the fibers are detected by a single detector producing an enhanced amplitude and frequency response compared to the narrowest commercially available interference filters.

Table 1. Specifications of Two-Element Lenses

Glass type: LASF9 (850322), grade 1, normal quality

Element 1:	$R_1 = 80.0 \text{ mm}$	Element 2:	$R_1 = \text{plane}$
	$R_2 = 50.0 \text{ mm}$		$R_2 = 133.0 \text{ mm}$
	$T = 6.0 \text{ mm}$		$T = 6.0 \text{ mm}$
	$D = 50.0 \text{ mm}$		$D = 50.0 \text{ mm}$

All surfaces are antireflective coated less than 1/2% between 750 and 850 nm, less than 3/4% between 525 and 850 nm.

To determine the number of useful equalizing fibers, the source spectrum, the wavelength-dependent fiber frequency response, the SPEQ lens characteristics, and the detector spectral response must be considered.

Where Cerenkov radiation is the source, with its peak production in the blue, the fiber attenuation and detector spectral response combine to make the peak broadband signal in the neighborhood of 800 nm for 1 km of fiber. The optimum wavelength for single-window fiber frequency response is approximately 850 nm for currently available commercial high bandwidth

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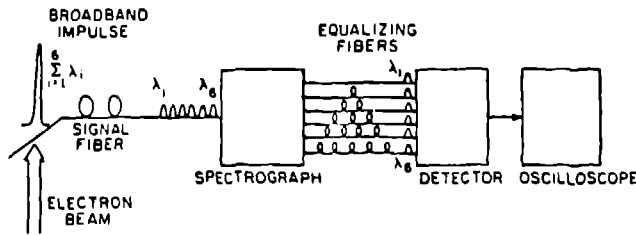


Fig. 2. Conceptual diagram of spectral equalization.

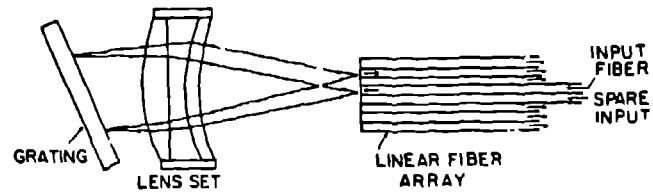


Fig. 3. Schematic of spectrograph.

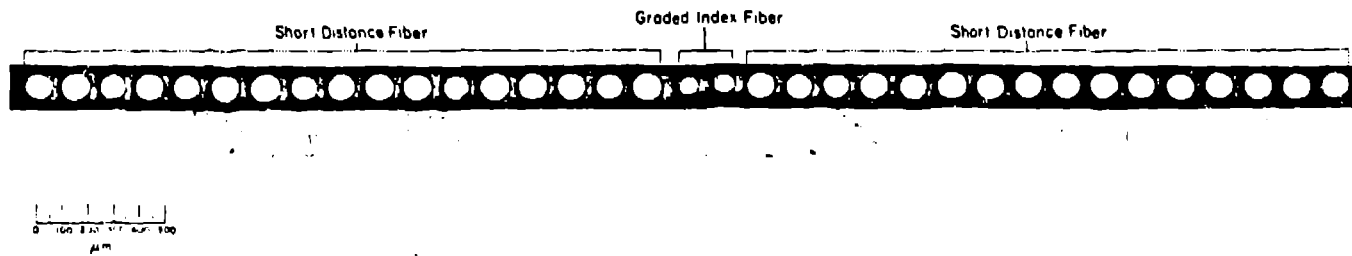


Fig. 4. Spectral equalizer fiber array.

fibers. The frequency response is increasing from 800 nm to the peak around 850 nm. However, from 800 nm toward shorter wavelengths the frequency response is rapidly decreasing. To use wavelengths much shorter than 800 nm will be detrimental to the frequency response. There is, however, an even stronger limitation on using the shorter wavelengths. The lens in the SPEQ was designed for minimum spherical aberration and a minimum acceptable number of glass-air interfaces. In order to achieve good coupling (better than 90% peak) with a two-element $f/1.55$, 77.3 mm focal length lens, glass with an index of refraction of 1.833 was used. This causes lateral chromatism and decreases the coupling efficiency most rapidly for shorter wavelengths. Figure 5 is a computer calculation of the peak coupling efficiency as a function of wavelength for various paraxial focal positions. The point of diminishing returns starts to be realized around 790 nm, a lower limit for the usable spectrum.

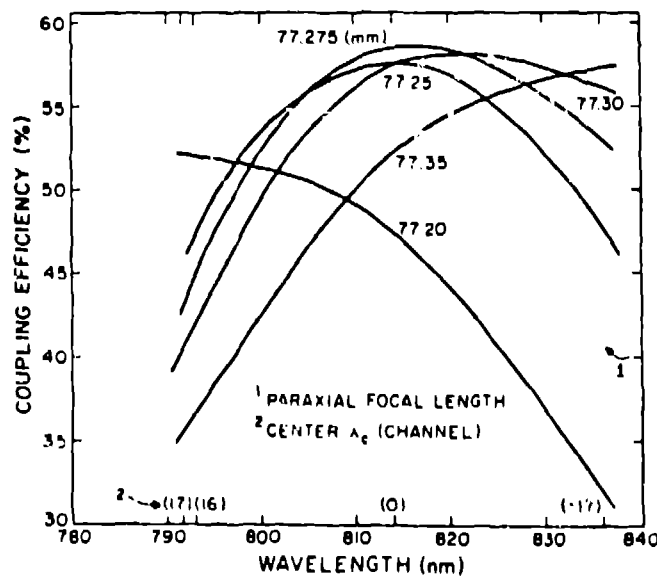


Fig. 5. Peak center wavelength coupling as a function of array paraxial focal position for $\lambda_0 = 814$ nm. Fibers are numbered consecutively from 17 to -17.

The upper limit is determined by the spectral response of the detector. For extended S-20 photocathodes the signal is a factor of 2 below peak amplitude by 840 nm and is dropping rapidly. Therefore, 840 to 850 nm become an upper limit. Recent MCP photocathode technology has made available GaAs surfaces that extends this upper region to 900 nm region. To determine the practicality of equalizing over a 50 nm spectral region the relative fiber lengths must be examined.

The maximum relative difference in equalizing fiber lengths for 1 km of signal fiber and a wavelength spread from 790 to 840 nm is 108 cm, with differences between adjacent fibers of about 3.0 cm. The equalizing fibers are trimmed and potted to an accuracy of ± 0.3 cm or ± 15 ps. This is well within the accuracy necessary for proper SPEQ performance.

With the introduction of low-frequency fibers (SDF) into a high-frequency system there is a question of frequency degradation. Modal dispersion in short lengths of fully excited, plastic clad, silica fiber has been measured to be 150 ps/m² with an NA near 0.4. In the equalizing fibers the modal volume being excited is the same as the input fiber (NA = 0.21) and much less than its total modal volume (NA = 0.3). It is also predominately the low-order modes that are excited, thus decreasing modal dispersion. Considering the ideal fiber profiles of the signal fiber ($\alpha \approx 2.0$ at 850 nm) and the equalizing fiber ($\alpha \approx 4.0$), the signal fiber behaves as an overcompensating fiber for modal distortion of wavelengths less than 850 nm. Calculations indicate the SDF fiber profile compensates for the modal distortion of the signal fiber up to a length of 15 m at which time the pulse starts spreading.⁹ Thus, if anything, the system frequency response is increased for short lengths of SDF fiber. Actual measurements of this phenomena are limited by the detector response time. In practice equalizing fiber lengths are less than 2 m.

Experimental results

The performance of the SPEQ was measured in a dc mode to check theoretical with experimental efficiency, and a pulsed mode to measure frequency response.

The theoretical average peak coupling efficiency of the spectral equalizer is 0.53 (Fig. 5). Experimental efficiency measurements were made using an LED. The proportion of LED spectrum used by the SPEQ was measured on an optical multichannel analyzer. The theoretical throughput is the product of the input connector transmission (0.79), the peak channel transmission (0.53), the channel FWHM (0.86 nm), and the number of channels (34), divided by the total usable spectrum (46 nm). The measured efficiency is the product of the input signal (85.8 $\mu\text{W}/\text{cm}^2$), the fraction of the spectrum used (0.60), and the fiber optic packing fraction (0.71), divided into the output (9.52 $\mu\text{W}/\text{cm}^2$). Theoretical efficiency is 0.27, experimental is 0.26. The excellent agreement between these is coincidental. Depending on the connector, array, and grating, this number could vary from 0.24 to 0.27. The efficiency is defined here as the fractional amount of available light that is utilized.

System frequency response measurements and amplitude enhancement data are presented in Table 2. Cerenkov radiation created in the fiber by a 50 ps FWHM electron beam from the EG&G/Santa Barbara linear accelerator was the optical source. An aluminum electron scatter plate was used to disperse the well collimated electron beam in angle to assure all fiber modes were excited. The signal was detected by a Varian MCP photomultiplier tube. The diagnostic system time response was 200 ps.

Table 2. Experimental Results of SPEQ Performance

<u>Spectral limiter</u>	<u>Fiber length (km)</u>	<u>Response (FWHM/ps)</u>	<u>Amplitude (mV)</u>
800/1.14 nm 55%*	1.0	400	10-20
SPEQ	1.0	300	125
SPEQ	0.8	222	-
SPEQ	0.63	210	-
SPEQ**	0.50	236	200

* Interference filter parameters.

** This is the only measurement made with the lens designed for the SPEQ. All other measurements were made with an 85 mm Olympus camera lens.

Conclusions

The concept of spectral equalization for optical fiber systems limited in frequency response by material dispersion has been described. The parameters that must be considered in designing and using a spectral equalizer have been described. A greater than 1 GHz-km frequency response system has been demonstrated using a fast spectrally broad Cerenkov light source, high-frequency-single window fiber, and state-of-the-art MCP photomultiplier tubes,

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and a SPEQ. The SPEQ was designed for use in the 790 to 850 nm region with each equalizing fiber equivalent to a 0.86 nm FWHM spectral width. Spectral equalizer systems have demonstrated a signal enhancement of more than 10 over a 1.14 nm, 55% transmitting, interference filter.

The basic concept is applicable to any broad spectrum source (an LED, for example) propagated over a long enough fiber for material dispersion to degrade system performance.

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