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ABSTRACT

The application of low loss multimode optical fibers to nuclear diagnostics has been discussed in previous papers.[1-3] Fiber requirements for this application differ substantially from those for normal communications use. The emphasis for nuclear measurements has been on development of high frequency analog fiber optic transmission line systems, which range from 100 MHz to >500 MHz signals transmitted at 600 nm and 800 nm, respectively. Accordingly, specialized fiber characterization procedures over a wide spectral range have been developed. These techniques include measurement of material and modal dispersion, optical attenuation, and optical linearity. It is also important to know the prompt radiation response of optical fibers in nuclear diagnostics. Measurements of this type have been discussed in previous papers.[4,5]

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INTRODUCTION

Optical fiber recording systems developed for nuclear diagnostics emphasize high frequency analog transmission. Systems typically include a radiation-to-light converter, optical fiber transmission link, detector such as photomultiplier tube (PMT) or microchannel plate (MCP), and oscilloscopes. Past and present sources of radiation-induced light include broadband fluors[6] that have maximum fiber-PMT systems sensitivity at 600 nm, and Cerenkov emitters with a maximum fiber-MCP detector system sensitivity at 800 nm. Another system utilizes a dye laser carrier that is emitting at 640 nm and is modulated by a radiation-driven optical modulator. The variety of wavelengths used, their unconventional spectral locations, and the frequency response required of the fibers have forced development of specialized characterization procedures.

Measurement of dispersion in a fiber is necessary for several reasons. Modal dispersion, for example, is the ultimate bandwidth-limiting property of a fiber. Material dispersion measurement is also necessary. A high bandwidth system utilizing a broadband light source must use optical filtration to minimize pulse broadening. The necessary filter characteristics are dictated by the degree of material dispersion and the system bandwidth specification. Further, it is necessary to know optical fiber transit times accurately for trimming and timing purposes. Transit times conventionally measured by optical time domain reflectometers are at 800 nm to 860 nm wavelengths, for instance, while transit times are longer at the shorter wavelengths of interest. We will describe techniques we have developed for evaluating dispersion.

With the variety of fibers presently available from different manufacturers, it is necessary to measure optical attenuation in a fiber for system design and,

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during system development and installation, to determine the best working wavelength and system losses. We will discuss two techniques for making attenuation measurements.

Systems using a modest-power dye laser to supply a light pulse for modulation must consider fiber linearity. Measurements of optical linearity have previously been reported.[7] We will briefly describe the measurement system and results.

MODAL AND MATERIAL DISPERSION

Measurement of material and modal dispersion is developed around analysis of a spectrally broad 50-psec Cerenkov light pulse launched near one end of a test fiber. The light pulses are generated by the DOE/EG&G electron linear accelerator (linac) which delivers a 50-psec burst of electrons at energies to 27 MeV, current densities to 100 A/cm^2, and repetition rates to 360 pps. A schematic diagram of this system is presented in Figure 1.

After traversing the fiber, the emerging Cerenkov pulse is passed through selectable narrow band optical filters and detected either by a statically focused crossed-field PMT with a cooled InGaAsP photocathode or, in cases where more limited spectral range is tolerable, an MCP detector. The output is then fed to the remote head of a sampling oscilloscope and displayed. Resolution of the system (~250 psec) is sufficient in most cases to measure to the modal dispersion limit for fiber lengths of interest. Fibers as long as 1.2 km have been measured. In fibers which demonstrate a permanent induced radiation absorption, the Cerenkov pulse is generated in a short auxiliary radiation-resistant fiber, such as plastic clad silica (PCS), attached to the test fiber.

Manufacturers design fibers to have highest frequency response around available sources and detectors, usually between 800 and 900 nm where fibers are generally used commercially. The optimum index profile for high frequency response in a fiber at 900 nm is a poor index profile for a system operating at 600 nm. This is illustrated by measurements of modal dispersion made on the linac with the previously described system. The results are given in Figure 2. Measurements were made through three graded-index (GI) fibers 1 km long using a 1-nm-wide spectral filter and detected with an MCP detector. Only the material dispersion due to the filter spectral width has been unfolded. Full width at half maximum (FWHM) of the system response was 358 psec.

The figure shows the pronounced increase in pulse broadening that occurs at the shorter wavelengths for fibers optimized in index gradient for near-IR transmission.

Modal dispersion at 600 nm is also measured with a mode-locked argon ion-pumped dye laser. The dye pulse width is 3 psec and its spectral width is 1 nm. A Pockels cell gates out single pulses from the modelocked cw pulse train. The pulse is launched into the optical fiber and detected by an ITT 100-psec response photodiode. The output is then fed to the remote head of a sampling oscilloscope and displayed. Resolution of the system through 1 km of fiber is limited by material dispersion to about 270 psec and through a short length is detector-limited to about 100 psec.

Material dispersion as a function of wavelength is measured by noting the arrival time of various pulses with different central wavelengths.[8] Figure 3 is an example of an unfiltered Cerenkov/fiber/detector spectrum measured with the previously described linac system. The OH radical absorption bands at 725, 825, 875, and 950 nm are clearly demonstrated along with the nonlinear scale relationship between wavelengths and time due to material dispersion.

The material dispersion ($\Delta t/l\Delta\lambda$) is:

$$\frac{\Delta t}{l\Delta\lambda} = \frac{t\Delta ch}{l\Delta\lambda}$$

where

t = time per channel

Δch = number of channels between known wavelengths

$\Delta\lambda$ = difference between known wavelengths

l = fiber length

Theoretical dispersion curves have also been calculated.[9] A three-element Sellmeier expression was employed using coefficients published by Fleming[10] of Bell Laboratories. All Corning fibers we have measured agree with the curve for 4.1% GeO_2 in SiO_2. ITT fibers have shown an approach to that curve as time progressed (and the bandwidth increased), but they still have higher dispersion and a slightly different curve shape. The good fit of the Corning data to the theoretical curve perhaps indicates that the gradient of doping across the fiber is not enough to make a significant change in dispersion.

Our data are an excellent fit to a power law throughout our commonly used wavelength range of 839 to 570 nm, which results from arrival time measurements of Cerenkov light pulses with filters at 60 to 70 nm intervals between 540 and 877 nm. The detector sensitivity limited us to this region in this measurement.

Table 1 sets forth our best data set; i.e., the points fall on a smooth curve with almost no scatter.

The error introduced by use of the 60- or 70-nm wavelength interval is negligible for the theoretical curves.

D_{cal} is from the best fit power law:

$$D_{cal}\ (\text{psec-nm}^{-1}\text{-km}^{-1}) = 2.194 \times 10^{12}\ \lambda^{-3.543}$$

T_{cal} is obtained from the integral times the length in km:

$$T_{cal}\ (\text{nsec}) = 8.63 \times 10^{8} \left(\frac{1}{\lambda_1^{2.543}} - \frac{1}{\lambda_2^{2.543}}\right) 0.578$$

It is not practical to get the power law from the arrival times directly because there is an additive constant, namely the transit time at 877 nm, which is imperfectly known.

Figure 4 compares Corning fiber with a high-dispersion ITT fiber. Between 630 and 840 nm the points for the ITT fiber lie on a power law curve that is very similar to that of SiO_2 + 13.5% GeO_2, but the two points at 919 and 1010 nm are significantly below the values calculated, which are in turn below the power law derived from the shorter wavelengths.

A more recent Cerenkov light dispersion measurement was made on the linac in conjunction with Corning personnel. The fiber was a special type, and a Ge avalanche photodiode detector was used to extend the spectral range to 1500 nm. The dispersion data are shown in Figure 5 to describe the smooth dispersion curve anticipated for this fiber.

ATTENUATION

Two techniques for determining fiber attenuation have been developed and used. A fiber analyzer instrument of the time domain reflectometer type has been developed which provides a single wavelength determination of average attenuation in the region of 850 nm.[11] The analyzer uses an injection laser as a probe pulse source and utilizes the back-scattered light signature from the fiber for the attenuation measurement.

Another attenuation measurement employs a continuum dc optical source and an optical multichannel analyzer (OMA) that operates in the 250- to 880-nm region. The spectral difference in the light transmitted through two fiber lengths is obtained directly with the OMA. An example of fiber attenuation in two graded-index fibers and a PCS fiber over the region 620 nm to 880 nm is shown in Figure 6.

OPTICAL LINEARITY

A flash-lamp-pumped dye laser, having wavelength of 595 nm, linewidth of 0.6 nm, pulse duration of 2 μsec, and peak power of 50 kW, was employed to investigate nonlinear optical transmission due to stimulated Raman scattering generated in a 510-m-long Corning multimode step-index fiber.[12] The first-order forward and backward stimulated Stokes emissions appeared as the peak injected powers reached 1.3 kW and 1.8 kW, indicating a linear power transmission limit for this fiber of about 1 kW each. At a peak pump power of 16 kW, up to six orders of forward Stokes emission and four orders of backward Stokes emission were observed, and the input wavelength component was severely depleted except the leading and trailing edges. In contrast, all four orders of backward Stokes emission were observed simultaneously. They were temporally separated, higher-order pulses following lower-order ones, and were all considerably steepened. These data are shown in Figure 7.

A 10-psec pulse switched out from the same dye laser, which was passively modelocked, was also used to study the stimulated Raman scattering and self-phase modulation in a 19-m-long multimode graded-index fiber. A continuum of over 200 nm wide was observed, as shown in Figure 8.

SUMMARY

Systems for characterizing optical fibers over the spectral region from 500 to 1500 nm have been developed. There are ongoing efforts to improve these techniques.

ACKNOWLEDGMENT

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Table 1. Bare Corning #30525103 578 m, 81.49 psec/channel

λ (nm)	Channel	D_m (psec-nm^{-1}-km^{-1})	D_{cal} (psec-nm^{-1}-km^{-1})	T_m (nsec)	T_{cal} (nsec)
877	220			--	--
839		96	96		
801	272			4.24	4.25
766		135	133		
730	340			9.78	9.76
695		185	183		
660	432			17.28	17.40
630		265	266		
600	545			26.48	26.67
570		381	379		
540	707			39.69	39.91

FIGURE CAPTIONS

1. Experimental setup for measurement of modal and material dispersion in optical fibers.

2. Modal dispersion measurements for three fibers.

3. Broadband Cerenkov spectrum through 1 km of fiber recorded with a cross-field PMT.

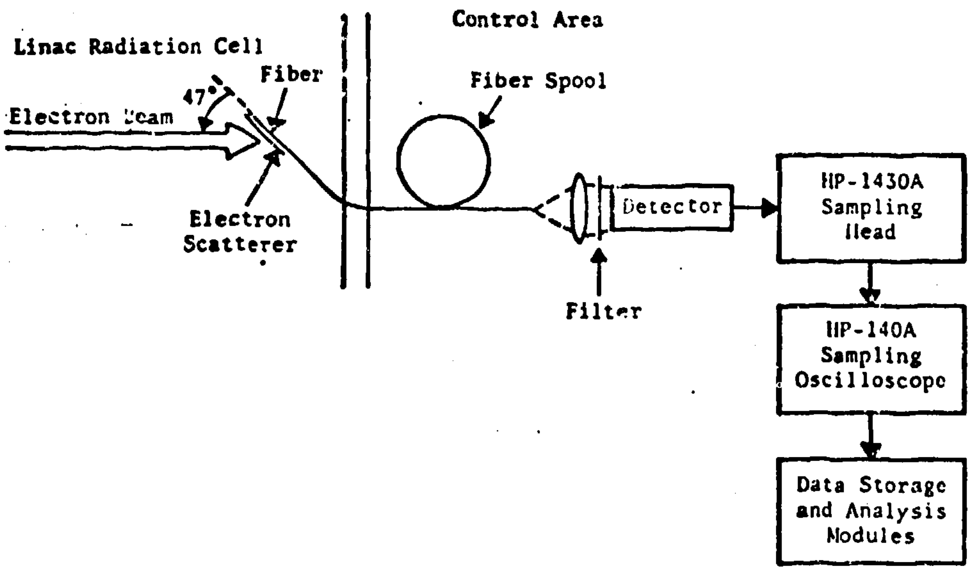
4. Comparison of material dispersion characteristic between Corning and ITT graded index fiber.

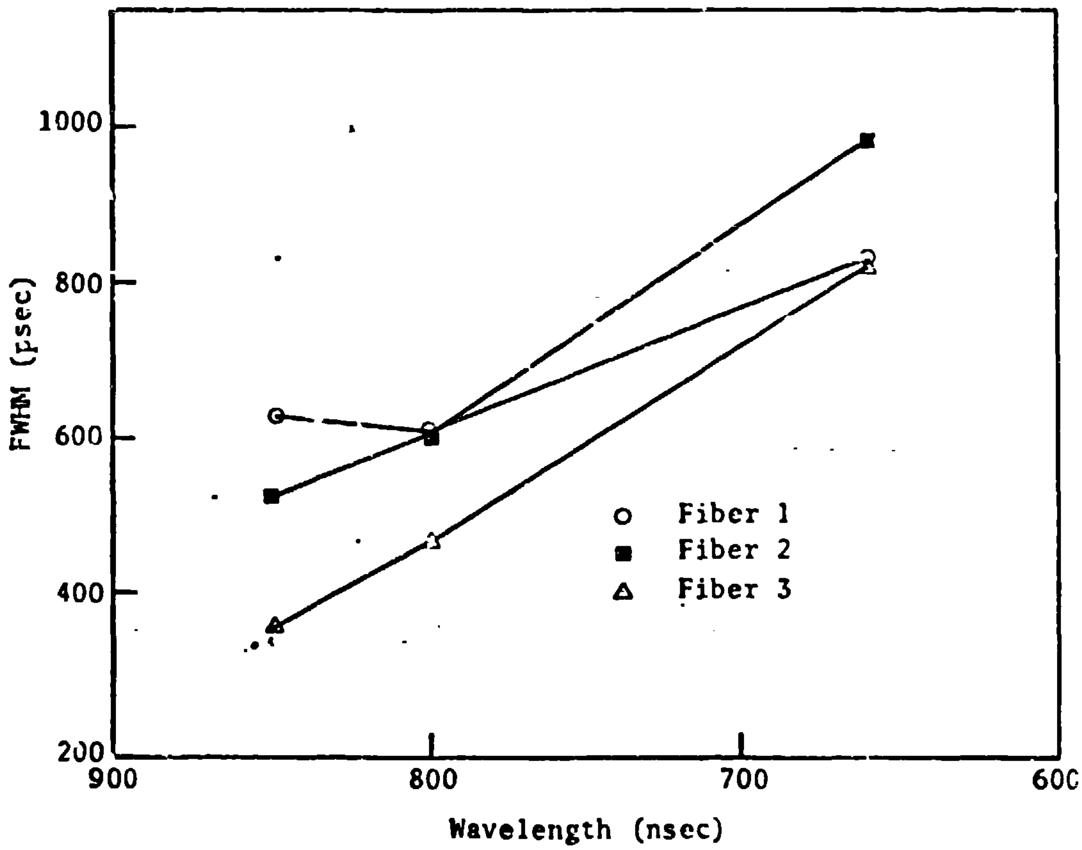
5. Transmission delay versus wavelength for two special Corning fibers.

6. Sample of attenuation in one PCS and two graded-index fibers.

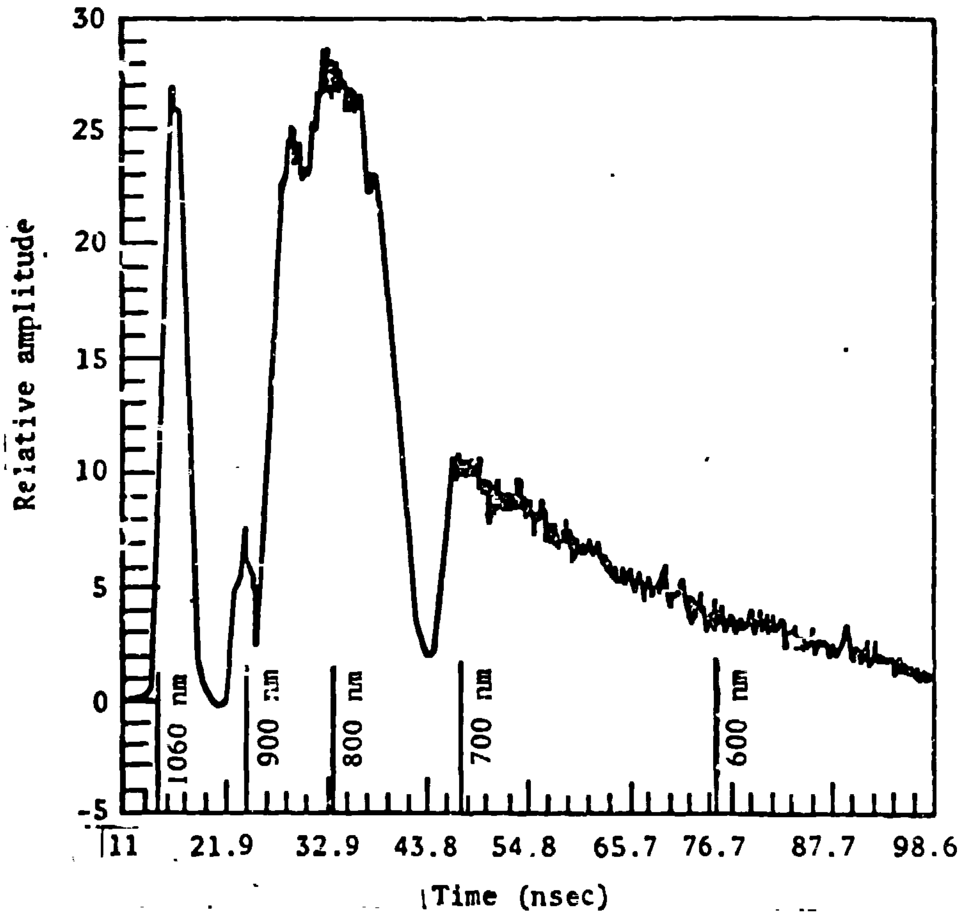
7. Backward stimulated Raman scattering generated by a flashlamp pumped dye laser pulse in 510-m-long multimode step-index fiber at a peak injected power of 15 kW. Top trace: Fresnel reflection of the incident laser pulse from the entrance surface of the fiber; bottom trace: backward stimulated Raman scattering. Three pulses generated successively are first-, second-, and third-order Stokes emission, respectively.

8. OMA display of continuum generated by a picosecond modelocked dye laser pulse in a 19-m-long multimode graded index fiber. Resolution of OMA is 0.55 nm/channel, and total coverage is 500 channels.

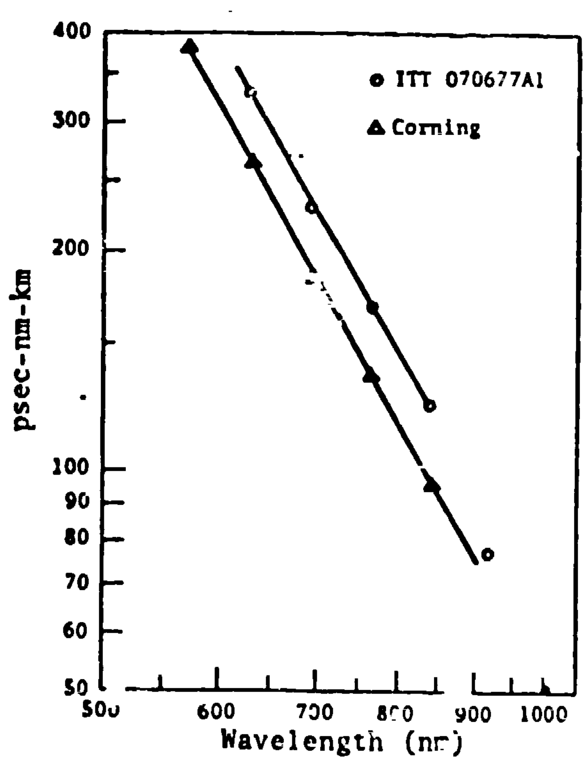

Control Area
Linac Radiation Cell
Fiber
47°
Electron Beam
Fiber Spool
Electron Scatterer
Detector
Filter
HP-1430A Sampling Head
HP-140A Sampling Oscilloscope
Data Storage and Analysis Modules



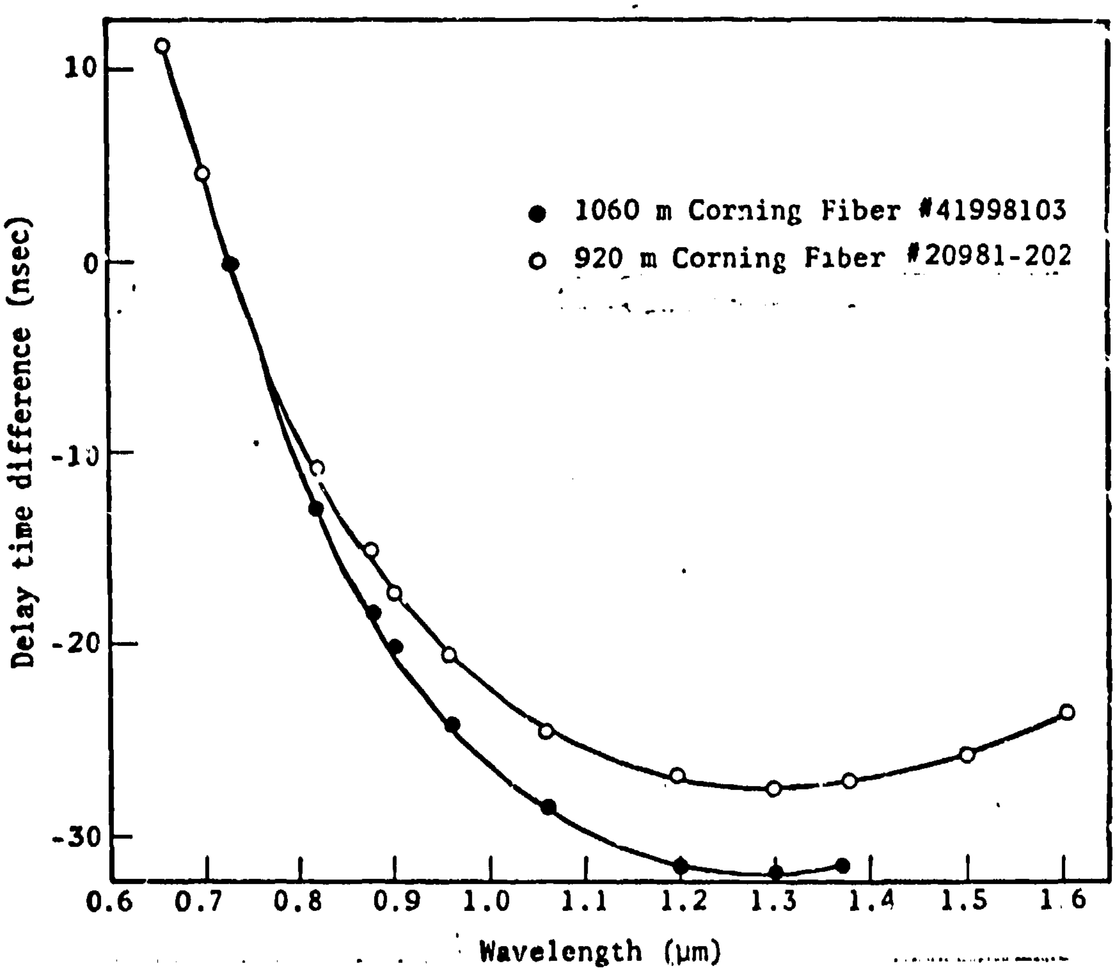
1000
800
600
400
200
900
800
700
600
FWHM (psec)
Wavelength (nsec)
Fiber 1
Fiber 2
Fiber 3



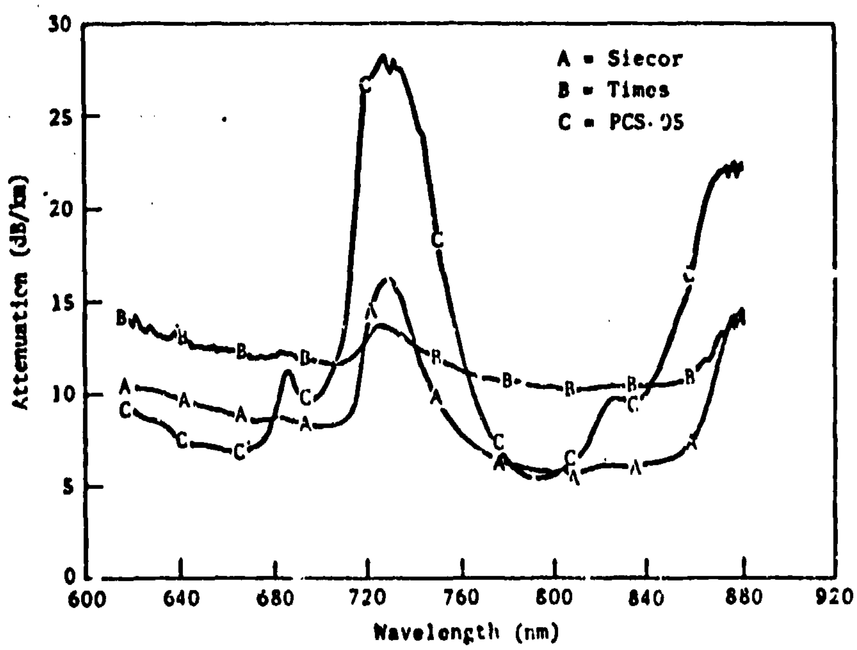
30
25
20
15
10
5
0
-5
Relative amplitude
1060 nm
900 nm
800 nm
700 nm
600 nm
11
21.9
32.9
43.8
54.8
65.7
76.7
87.7
98.6
Time (nsec)



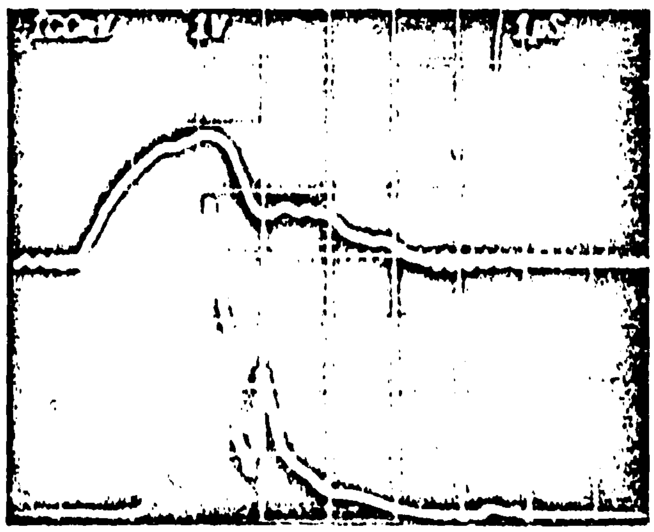
400
300
200
100
90
80
70
60
50
psec-nm-km
ITT 070677A1
Corning
500
600
700
800
900
1000
Wavelength (nm)



1060 m Corning Fiber #41998103
920 m Corning Fiber #20981-202
Delay time difference (nsec)
Wavelength (μm)
10
0
-10
-20
-30
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6



A = Siecor
B = Times
C = PCS-95
Attenuation (dB/km)
Wavelength (nm)


1V