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Wavelength Dependent Measurements of Optical Fiber Transit Time, Material Dispersion, and Attenuation

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A new method for measuring the wavelength dependence of the transit time, material dispersion, and attenuation of an optical fiber is described. We inject light from a 4-ns risetime pulsed broadband flashlamp into various length fibers and record the transmitted signals with a time-resolved spectrograph. Segments of data spanning an approximately 3000 Å range are recorded from a single flashlamp pulse. Comparison of data acquired with short and long fibers enables the determination of the transit time and the material dispersion as functions of wavelength dependence for the entire recorded spectrum simultaniously. The wavelength dependent attenuation is also determined from the signal intensities. The method is demonstrated with experiments using a step index 200-μm-diameter SiO_2 fiber. The results agree with the transit time determined from the bulk glass refractive index to within ± 0.035% for the visible (4000-7200Å) spectrum and 0.12% for the ultraviolet (2650-4000Å) spectrum, and with the attenuation specified by the fiber manufacturer to within ± 10%.

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I. Introduction

Fiber optics are used to diagnose many short-duration, high-energy-density physics experiments including laser plasma, z-pinch, ion beam, and shock wave investigations. The fibers typically transmit light over 10-100 m distances from the experiment to a remote detection system. Two requirements in these experiments are nanosecond time resolution and accurate understanding of the signal intensities. Thus, characterization of the fiber properties that impact these parameters is necessary. The diagnostic targeted by the characterization measurements described in this paper is optical spectroscopy. In this application, light emission from a hot plasma or shock-heated solid is transported to a remote time-resolved spectrograph [1,2]. Interpretation of the resultant data requires knowledge of the attenuation and fiber transit time as a function of wavelength.

The transit time τ for a single mode to travel a distance L, at a wavelength λ, in a fiber is determined by the group velocity [3],

$$\tau = \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right) \quad \text{Eq. 1}$$

where n is the refractive index and c is the speed of light in vacuum. The material dispersion is then defined [3] as

$$\frac{d\tau}{d\lambda} = -\lambda\frac{L}{c}\frac{d^2n}{d\lambda^2} \quad \text{Eq. 2}$$

The transit time τ, sometimes known as the group delay time, specifies the variation in transit time at different wavelengths, while the material dispersion determines the temporal pulse spreading at a given wavelength. For optical spectroscopy, it is crucial to know $\tau(\lambda)$ since different wavelengths of light from a single event arrive at different times and alter the apparent time history of the spectrum. On the other hand, it is less important to know $d\tau/d\lambda$ for optical spectroscopy. The wavelength interval $d\lambda$ is usually small enough that the pulse broadening due to material dispersion is negligible. Instead, the pulse broadening at a given wavelength is dominated by intermodal dispersion. The intermodal dispersion is due to the variation in the group delay among the different modes that propagate in the fiber. For other diagnostics, such as x-ray imaging with scintillators [4], the material dispersion is important since there is no dispersive element that distinguishes one wavelength from another.

In principle, the fiber transit time and material dispersion can be determined from the bulk refractive index of the glass used to construct the fiber. However, the possibility of changes in the glass properties due to impurities or thermal stresses introduced during fabrication makes it desirable to measure the properties of the fiber itself. The fiber attenuation can be readily measured with a continuous wave light source filtered to provide a controlled wavelength. A variety of methods exist to measure the fiber transit time [5-10]. The most straightfoward is to split a monochromatic light pulse, inject it simultaneously into two lengths of fiber, and measure the difference between the transit times [8-10]. This light source could be a pulsed laser or a flashlamp equipped with suitable bandpass filters. In our experiments, we first use the flashlamp method to measure the absolute fiber transit time at 4000Å, 6700 Å, and 8500 Å. This method provides accurate results but it is not practical for performing measurements on large numbers of wavelengths. However, in optical spectroscopy the need exists for continuous information over a broad range of wavelengths. This paper describes a method developed to satisfy that need.

In our technique the unfiltered light from a pulsed flashlamp is injected into a fiber and the transmitted light is recorded with a time-resolved optical spectrograph. The spectral range covered in a single pulse is typically 3000 Å. Using a single pulse injected into one fiber, rather than splitting the pulse and injecting simultaneously into two fibers, prevents measurement of the absolute fiber transit time. However, by comparing data recorded with different fiber lengths we can determine the relative fiber transit time as a function of wavelength. The wavelength-dependent transit time is then placed on an absolute scale using absolute data taken at a few wavelengths. Dividing the signal intensity obtained with a long fiber by the intensity obtained with a short fiber gives a measure of the fiber attenuation. We compared our results with data supplied by the fiber manufacturer and found that the fiber transit time agreed within $\pm$ 0.035% over the 4000 - 7200 Å range. The attenuation was also in reasonable agreement.

II. Experiment

A. Absolute Transit Time Measurements

We measured the absolute fiber transit time at three different wavelengths, 8500 Å, 6700 Å, and 4000 Å. The fibers tested [11] were fused silica radiation-hardened step index fibers with 100 µm core and 125 µm clad diameters. The measurements at 8500 Å used two fibers connected to a single 1 ns full width at half maximum (fwhm) pulsed laser diode. The measurements at 6700 Å and 4000 Å were performed with a 4-ns-risetime 20-ns-fwhm broadband pulsed flashlamp [12]. A 100-Å-fwhm bandpass filter centered at either 6700Å or 4000 Å selects the wavelength. The light was coupled into the fibers using a diffuser/lens configuration that ensures overfilling. A beam splitter enables injection into both fibers simultaneously. At all three wavelengths, the fiber lengths used were 4.60 m and 106.78 m. Both fibers were simultaneously connected to an 800-ps-risetime photomultiplier tube (PMT) and the transmitted signals were recorded on a Tektronix 640A oscilloscope which has a 0.98ns rise time [13]. The transit time for the laser diode measurement was determined using the centroid of the 1 ns fwhm peak. The transit time for the flashlamp measurement was determined from the 50% intensity point on the rising edge.

The fiber transit time obtained in these measurements is shown in Figure 1. The transit time is divided by the fiber length for convenience in applying the results to other experiments. Superimposed on the data is the transit time calculated from Eqn. 1 using the bulk glass refractive index supplied by Herasil Amersil [14]. Our results are 0.18%, 0.28%, and 0.13% higher than the curve computed from the refractive index at the 4000Å, 6700Å, and 8500Å wavelengths, respectively. We regard this as excellent agreement as the manufacturer's data is accurate to $\pm 3*10^{-5}$. It is unclear if the difference is due to systematic errors in our measurements or if it is because the actual fiber refractive index is slightly different than the bulk glass refractive index. Systematic errors could arise from the measurement of the difference between the transit times of the two fibers. For example, at 8500Å the difference between the transit times for the two fibers was

500.41 ns, compared to 499.75 ns from the calculation based on the refractive index. Such discrepancies could result from an oscilloscope calibration error, or from the accuracy of determining the centroid of the pulsed laser diode or the 50% intensity time for the pulsed flashlamp. We consider the latter possibility to be unlikely since the discrepancy is similar for the two methods.

Systematic errors could also result from the measurement of the fiber lengths. In these experiments the lengths of the fibers to be tested were measured using an optical time domain reflectometer (OTDR) that was calibrated using fibers of a known physical length. The physical length is measured with a tape measure to within 0.017%. The OTDR measures the fiber transit time using a pulsed laser diode at 8500 Å and provides a length based on a user-supplied refractive index. For high accuracy, it is important to input

$$n - \lambda\frac{dn}{d\lambda} \qquad \text{Eq. 3}$$

as specified in Eqn. 1 rather than simply using n. At the 8500Å OTDR wavelength, Eqn. 3 is a factor 1.00948 larger than n for all fiber lengths. After taking this into account, the OTDR lengths were found to be a factor of 1.00428 longer than the physical lengths. The remaining discrepancy between the OTDR and physical length measurements may be because of OTDR calibration errors.

Another possibility is that the optical path is slightly longer than the distance along the fiber core. The power in the fiber is distributed among many modes that reflect numerous times from the core/clad interface, leading to a variation in the group delay between the modes. That is, each mode has a slightly different group delay. The physical measurement of the fiber only measures the fiber core length, while the light may travel along the fiber with up to 12^o of deflection. If all of the remaining error is assumed to be from group delay, the mean of the power is being carried by the 5.29^o ray path. An investigation of the modal power distribution was beyond the scope of the present study. The lengths used in the results reported here correspond to measurements with the OTDR, corrected by a factor of 1.00428 to agree with the physical length.

B. Spectrograph measurements

The measurement of the relative fiber transit time and fiber attenuation over the 2650 Å to 7200 Å range is accomplished using the fast pulsed flashlamp and a time-resolved spectrograph. The experiment setup for 3900-7200 Å visible regime is shown in Figure 2. Extension into the ultraviolet is described below. A 35 mm focal length f/1.2 achromatic Nikon lens couples light from the 4-ns-risetime flashlamp into a 2-m-long 200-μm-diameter step index fiber. Before performing any fiber characterization tests we first verify that this 2 m fiber is overfilled. This is done with a photodiode mounted on a rotation stage to measure the angular distribution of the light exiting the fiber.

The fiber characterization test consists of connecting a known fiber length between the flashlamp fiber and a time-resolved spectrograph (see Figure 2). This 200-μm-diameter step index fiber [11] is formed from the same glass and has the same numerical aperture as the 100-μm-diameter fiber used for the absolute transit time measurements. The spectrograph is similar to instruments developed for pulsed plasma spectroscopy [1]. It uses a 2/3 m Czerny-Turner spectrograph with a streak camera located in the exit focal plane. A 150 l/mm f/4 grating blazed at 5000 Å provides 97Å/mm reciprocal dispersion. The time resolution provided by the ~ 5ns/mm sweep was about 0.5 ns, although the precision of locating the 50% intensity level on the rising edge was significantly better.

The data recorded from a single flashlamp pulse for each fiber is an image with wavelength and time displayed as the axes (Fig. 3). Superimposed on each image are wavelength and time fiducials. As the test fiber length is increased, the streak camera is triggered later to account for the increased fiber transit time. The flashlamp jitter is a few nanoseconds, making the absolute time between images recorded with different length fibers an unreliable means of measuring the fiber transit time. Therefore, our strategy is to use this data to measure only the relative transit time as a function of wavelength. The flashlamp spectrum consists of lines and continuum and is related to the plasma conditions created in the lamp. In general, the emission intensity history from the flashlamp may vary with wavelength. That is, the 50% intensity may occur at different times at different wavelengths, depending on such factors as the plasma temperature and density evolution, and whether spectral lines are located at that wavelength. The recorded spectrum may also be slightly distorted by streak camera imperfections. To ensure that these factors do not impact the relative fiber transit time measurements, we compare data from a long fiber to data with a short test fiber, using the assumption that the only difference between data taken with the long and short fibers is the extra transit time and attenuation introduced by the extra fiber length.

The analysis procedure begins by taking a sequence of time-direction lineouts using a 45 Å wide wavelength interval. Seventy lineouts are taken on each image. A typical lineout is shown in Fig. 4a. Each lineout is smoothed using a fast Fourier transform filter that removes high frequency noise. The time corresponding to the 50% intensity is then determined. Next, a plot is constructed of the relative transit time as a function of wavelength (Fig. 4b). This process is followed for all the tested fiber lengths. Fig. 4b shows that for a 4.12 m test fiber the 4000 Å light is delayed by about 3.75 ns relative to the 7000 Å light. Approximately 0.6 ns of this delay is due to the wavelength dependence of the transit time, based on results displayed in Fig. 1. The rest is due to a combination of delayed short wavelength emission by the flashlamp and streak camera imperfections. It is clear from Fig. 3b and 4b that the transit time difference between 4000 Å and 7000 Å is much greater with a 181.08 m long test fiber. Note that in Fig. 4b the absolute difference between the two curves is unimportant. The two curves have been arbitrarily shifted to enable display on the same graph. What is significant is the difference between the relative transit times as a function of wavelength. The relative transit time as a function of wavelength is determined for 181.08-4.12 = 176.96 meters of fiber by subtracting the two curves in Fig. 4b and dividing by the 176.96 m difference in lengths. The red curve in Figure 1 shows the relative transit time curve, placed on an absolute scale using the value of the delay computed with Eqn. 1 from the refractive index at 6700Å. The choice of using 6700Å relies on the fact that the transit time changes more slowly at the red end of the spectrum, minimizing any possible errors. Using the value at one specific wavelength as calculated from the refractive index, rather than the actual absolute measurements, was motivated by the desire to compare the shape of the relative transit time measurement to the calculation and is justified by the small difference between the absolute measurements and calculation. The material dispersion, derived by taking the derivative of a curve fit to this data with respect to wavelength, is shown in Figure 5. Once again we superimpose the curve based on the bulk glass refractive index.

We used a similar procedure to measure the relative fiber transit time in the ultraviolet (UV). The spectrograph setup was the same as for the visible measurements except that the center wavelength was set at 4000 Å. In this mode, data with useful signal intensities was obtained over the 2650 Å- 5500 Å range in a single pulse. For the UV measurements no lens was used to couple the light from the lamp into the fiber. This choice was dictated by the lack of an achromatic lens over the 2650 - 5500 Å wavelength range and the fact that using a lens focused at one particular wavelength implies defocussing at the other wavelengths. The proximity coupling of the light may mean the fiber was underfilled. However, the UV measurements agreed with the visible measurements over the 3900-5500 Å range where they overlap, indicating that the effect of possible fiber underfilling was negligible. The fiber lengths tested in the UV were 0.66m, 24.25 m, and 50.11 m. The relative transit time was determined from the difference between the 50.11m and 24.25m fibers, the 24.25m and 0.66 m, and the 50.11m and 0.66 m long fibers. These lengths were shorter than in the visible regime measurements because the increased attenuation in the UV reduces the signal obtained if the fiber is too long. In addition, the transit time is longer at shorter wavelengths so a shorter fiber can provide adequate time difference accuracy. The transit time results are placed on an absolute scale by comparison with the time computed from the refractive index at 4000Å and displayed in Figure 1. The material dispersion is shown in Figure 5.

In the raw data the precision of measuring the time corresponding to the 50% intensity level at any given wavelength is ultimately limited by the streak tube photoelectron statistics. However, the analysis method here compares data after smoothing by a Fourier transform filter. Since this is a relative measurement, the value of the transit time is measured with respect to some reference wavelength (e.g., 6700 Å in the visible). After smoothing, data at each wavelength is compared with data at the reference wavelength. The smoothed data may be regarded as an approximate representation of the true shape of the flash lamp intensity history. The shape of the lamp history varies from one wavelength to another, but in principal the shape at a given wavelength is independent of the fiber length. In reality, the representation of the shape by the smoothed data at a particular wavelength may be expected to vary from one exposure to another, due to non-ideal effects. Thus, the uncertainty at a given wavelength depends on variations in the quality of the intensity history between exposures recorded with a short fiber and exposures recorded with a long fiber, as represented by the smoothed data. Such variations are difficult to quantify and a rigorous determination of the uncertainty in the relative transit time was not performed. However, the relative transit time data was found to agree with the calculation based on the bulk glass refractive index to within ±0.035% over the 4000-7200Å range and ± 0.12% averaged over the 2650Å-5500Å range. This agreement is consistent with the interpretation that the fiber refractive index is the same as the bulk glass refractive index and that the uncertainty in our measurements is approximately ± 0.035% in the visible and ± 0.12% in the UV.

III. Attenuation

The time resolved flashlamp spectra can also be used to determine the relative fiber attenuation as a function of wavelength. The flashlamp intensity may vary from pulse to pulse and, thus, these data are not suitable for determining the absolute attenuation. However, the relative attenuation as a function of wavelength can be determined by dividing the signal intensity obtained with a short fiber length by the signal intensity obtained with a long fiber. This intensity difference corresponds to the attenuation due to the extra length in the longer fiber.

The attenuation in the fiber is obtained from.

$$A(\lambda) = 10Log_{10}\left(\frac{P_i(\lambda)}{P_o(\lambda)}\right) \quad \text{Eq. 3}$$

The wavelength dependent intensities transmitted through the short and long fibers are P_i and P_o respectively. P_i and P_o are measured with two successive flashlamp pulses on two separate time resolved spectral images. The first step in our analysis is to derive A(λ) ignoring any differences between the injected flashlamp intensity from one pulse to another. This is expected to be a true representation of the wavelength dependence of the attenuation, but if the incident flashlamp intensity varies, then the absolute magnitude is incorrect. Therefore, we shift the magnitude of the entire attenuation curve to minimize the difference between our data and the results provided by the manufacture in references 11 and 14. The results are converted into an attenuation per unit length and displayed in Figure 6.

The amplitude adjusted experimental data in the visible (3900-7200Å) agrees with the manufacturer's data to within 9.0%. The UV data below 3800Å has an average deviation of 7.0% while the UV data above 3800Å has an average deviation of 26.0%. The error bars on the UV data show the standard deviation between the three sets of UV data. One possibility for the discrepancy in errors for the UV data is that the attenuation above 3800Å is small enough that a larger difference between fiber lengths is required to accurately measure it.

IV. Summary

We have presented a new method for determining the wavelength dependence of the fiber-optic transit time for a continuous range of wavelengths between 2650 and 7200 Å. High accuracy is obtained. An added benefit is that the material dispersion and attenuation can be determined from the same data. Further refinements of the method could include using a short duration laser plasma light source to improve the timing accuracy and enable extension to shorter wavelengths. In addition, absolute measurements, rather than relative ones, can be obtained by splitting the light pulse, simultaneously injecting it into a short and long fiber, and recording the transmitted signal on two separate time-resolved spectrographs.

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Figure Captions

Figure 1. Transit time per unit length. The * symbol represents the absolute measurements performed at 4000, 6700, and 8500Å. The red, yellow, blue, and magenta curves are measurements performed with the time resolved spectrograph. The black curve was derived from the bulk glass refractive index.

Figure 2. Experimental Setup

Figure 3. Flash lamp spectra recorded after transmission through 4.12m (top) and 181.08m (bottom) long optical fiber.

Figure 4a. Lineout averaging over 45Å interval centered at 5156Å, from the 181.08m long fiber data shown in Figure 3. The smooth curve is a FFT of the data.

Figure 4b. Relative transit time for two different fiber lengths. The actual distance between the two lines is irrelevant.

Figure 5. Material dispersion obtained by differentiating the curves displayed in Figure 1. Red is the dispersion of the visible data. Magenta, orange, and blue are the UV data sets, and black is the dispersion of the manufacture's data.

Figure 6. Experimental and Manufacturer's visible light attenuation. Blue is the adjusted UV attenuation and red is the adjusted visible attenuation. Black is the manufacturer's listed attenuation.

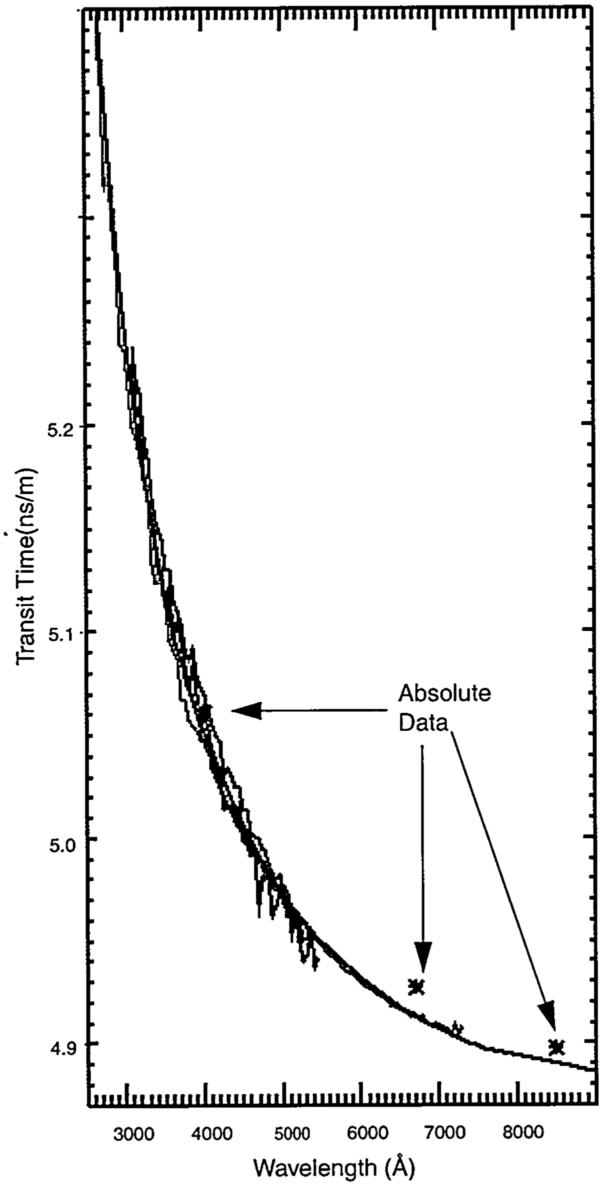

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Figure 1

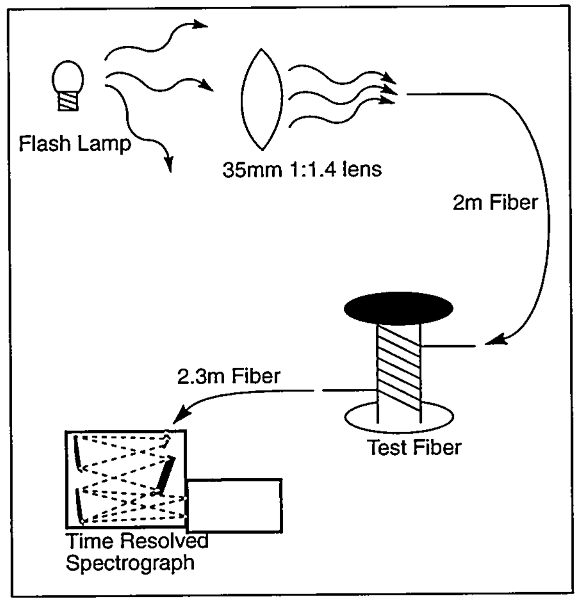

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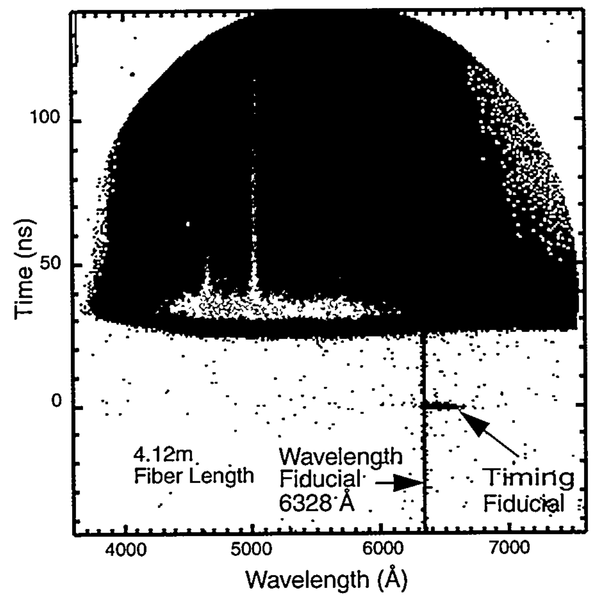
Figure 2.



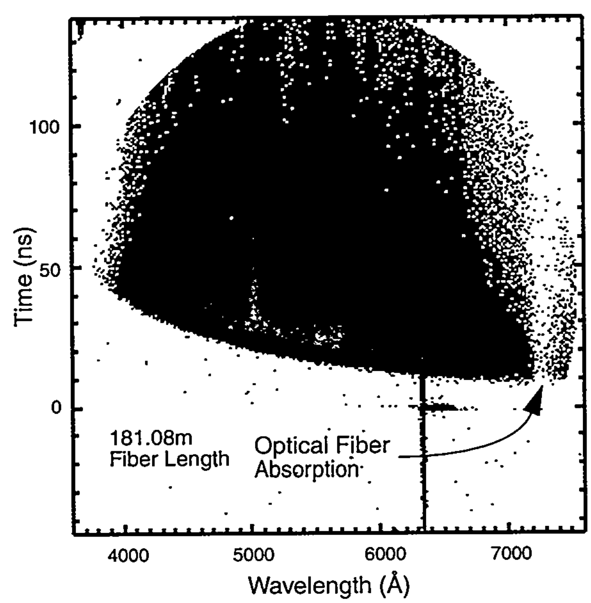


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Figure 3.

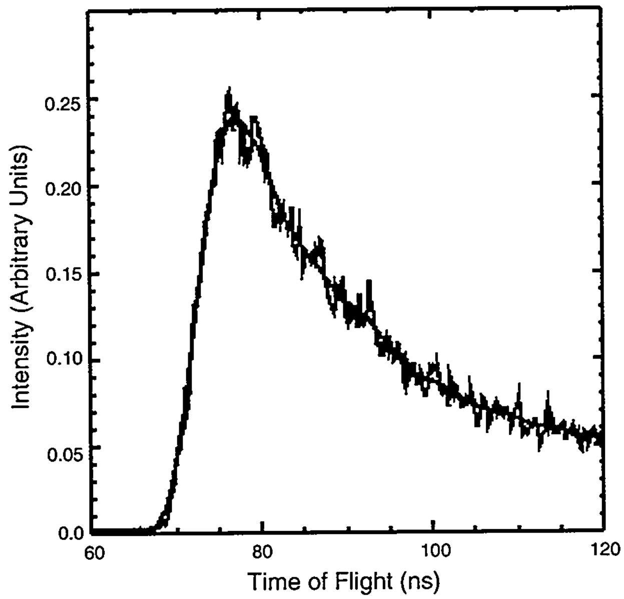

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Figure 4a.

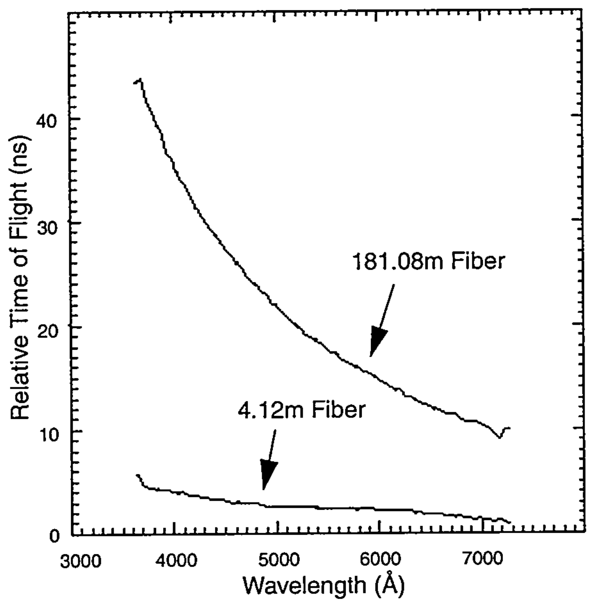

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Figure 4b.

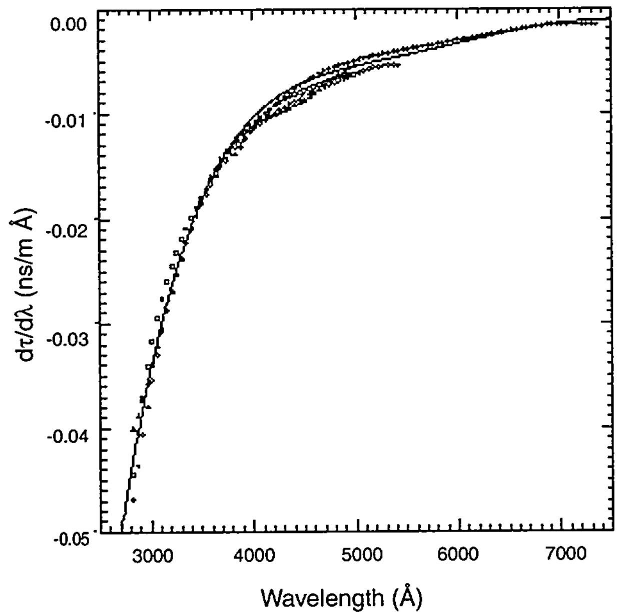

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Figure 5

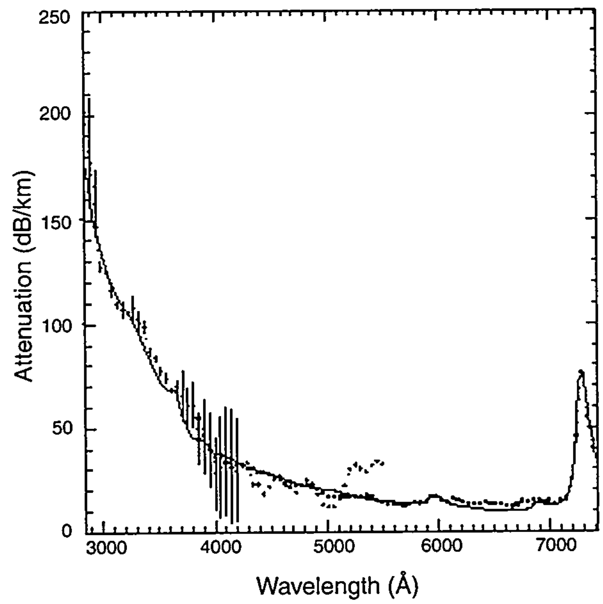

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Figure 6