Wavelength-dependent measurements of optical-fiber transit time, material dispersion, and attenuation

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A new, to our knowledge, 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 rise-time pulsed broadband flash lamp into fibers of various lengths and record the transmitted signals with a time-resolved spectrograph. Segments of data spanning a range of approximately 3000 Å are recorded from a single flash-lamp 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 simultaneously. 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 (4000–7200-Å) spectrum and 0.12% for the UV (2650–4000-Å) spectrum and with the attenuation specified by the fiber manufacturer to within ±10%. © 2001 Optical Society of America

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1. 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 affect 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 a 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]

$$\tau = \frac{L}{c}\left(n - \lambda \frac{\mathrm{d}n}{\mathrm{d}\lambda}\right), \tag{1}$$

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

$$\frac{\mathrm{d}\tau}{\mathrm{d}\lambda} = -\lambda \frac{L}{c} \frac{\mathrm{d}^2 n}{\mathrm{d}\lambda^2}. \tag{2}$$

The transit time τ, sometimes known as the group delay time, specifies the variation in transit time at different wavelengths, whereas 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. However, it is less important to know $\mathrm{d}\tau/\mathrm{d}\lambda$ for optical spectroscopy. The wavelength interval $\mathrm{d}\lambda$ is usually small enough that the pulse broadening that is 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 scintil-

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lators,[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 straightforward 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 flash lamp equipped with suitable bandpass filters. In our experiments we first use the flash-lamp method to measure the absolute fiber transit time at 4000, 6700, 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 flash lamp 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 with 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 to within ±0.035% over the 4000–7200-Å range. The attenuation was also in reasonable agreement.

2. Experiment

A. Absolute Transit Time Measurements

We measured the absolute fiber transit time at three different wavelengths, 8500, 6700, 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 FWHM pulsed laser diode. The measurements at 6700 and 4000 Å were performed with a 4-ns-rise-time 20-ns-FWHM broadband pulsed flash lamp.[12] A 100-Å-FWHM bandpass filter centered at either 6700 or 4000 Å selects the wavelength. The light was coupled into the fibers with 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 and 106.78 m. Both fibers were simultaneously connected to an 800-ps-rise-time photomultiplier tube and the transmitted signals were recorded on a Tektronix Model 640A oscilloscope, which has a 0.98-ns rise time.[13] The transit time for the laser diode measurement was determined with the centroid of the 1-ns-FWHM peak. The transit time for the flash-lamp measurement was determined from the 50% intensity point on the rising edge.

The fiber transit time obtained in these measurements is shown in Fig. 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 Eq. (1) with 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 4000-, 6700-, and 8500-Å wavelengths, respectively. We regard this as excellent agreement, because the manufacturer's data is accurate to $\pm 3 \times 10^{-5}$. It is unclear whether 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 8500 Å the difference between the transit times for the two fibers was 500.41 ns, compared with 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 flash lamp. 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 with an optical time-domain reflectometer (OTDR) that was calibrated with fibers of a known physical length. The physical length is determined 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

$$n - \lambda \frac{\mathrm{d}n}{\mathrm{d}\lambda} \tag{3}$$

as specified in Eq. (1) rather than simply using n. At the 8500-Å OTDR wavelength, Eq. (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

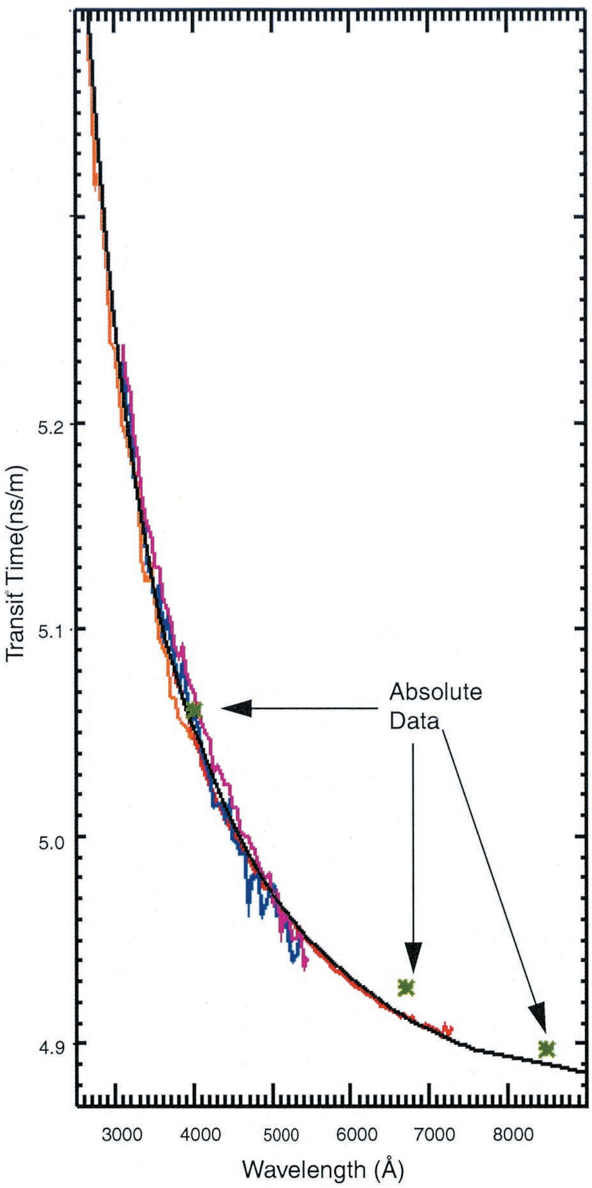

Fig. 1. Transit time per unit length. The green asterisk represents the absolute measurements performed at 4000, 6700, and 8500 Å. The red, yellow, blue, and magenta curves are measurements performed with the time-resolved spectrograph. The black curve was derived from the bulk glass refractive index.

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 measures only the fiber core length, whereas the light may travel along the fiber with as much as 12° of deflection. If all the remaining error is assumed to be from group delay, the mean of the power is being carried by the 5.29° ray path.

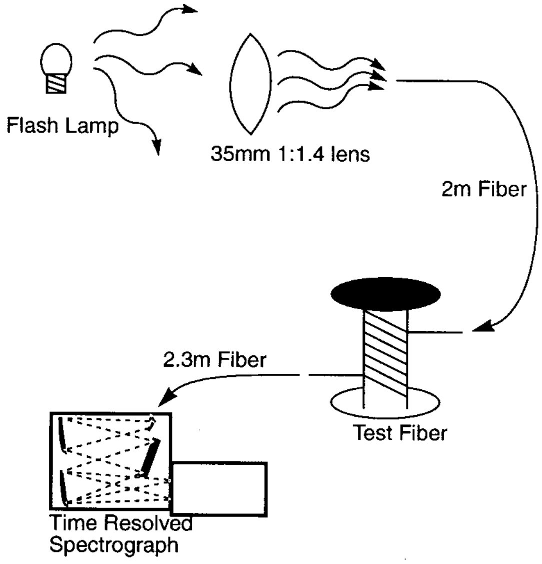

Fig. 2. Experimental setup.

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 2650–7200-Å range is accomplished with the fast pulsed flash lamp and a time-resolved spectrograph. The experimental setup for the 3900–7200-Å visible regime is shown in Fig. 2. Extension into the UV is described below. A 35-mm-focal-length $f/1.2$ achromatic Nikon lens couples light from the 4-ns-rise-time flash lamp 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 flash lamp fiber and a time-resolved spectrograph (see Fig. 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 1/mm $f/4$ grating blazed at 5000 Å provides 97 Å/mm reciprocal dispersion. The time resolution provided by the ~5 ns/mm sweep was ~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 flash-lamp pulse for each fiber is an image with wavelength and time

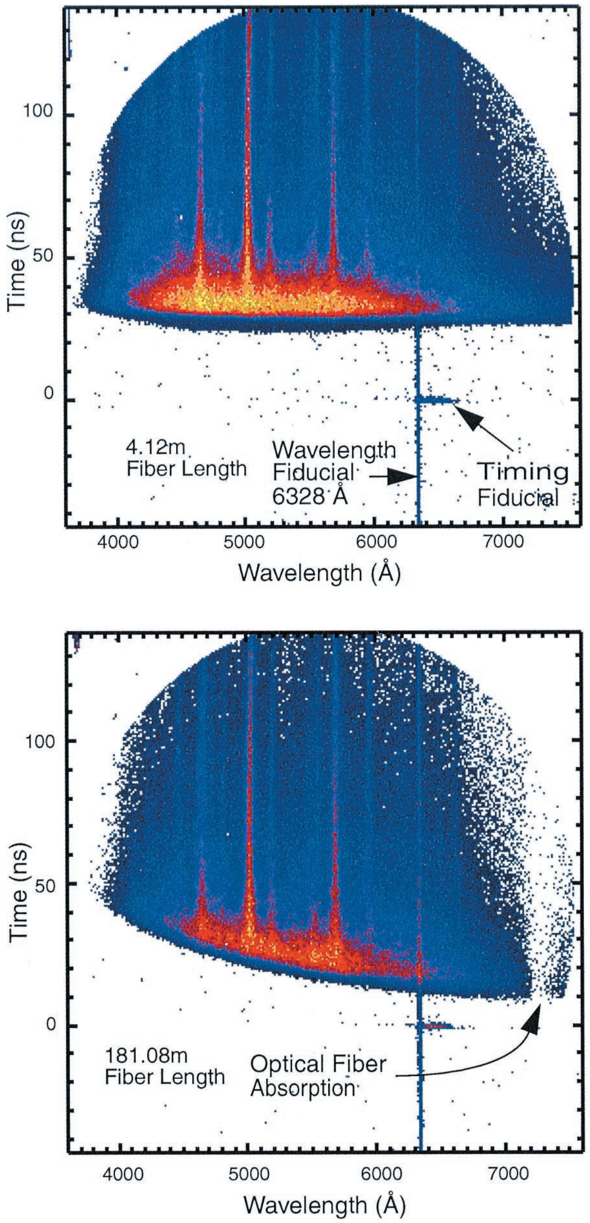

Fig. 3. Flash-lamp spectra recorded after transmission through 4.12-m-long (top) and 181.08-m-long (bottom) optical fiber.

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 flash lamp 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 flash-lamp 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 flash lamp 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 affect 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 the 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 with a 45-Å-wide wavelength interval. Seventy lineouts are taken on each image. A typical lineout is shown in Fig. 4(a). Each lineout is smoothed with 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. 4(b)]. This process is followed for all the tested fiber lengths. Figure 4(b) shows that for a 4.12-m test fiber the 4000-Å light is delayed by ~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 flash lamp and streak camera imperfections. It is clear from Figs. 3(b) and 4(b) that the transit time difference between 4000 and 7000 Å is much greater with a 181.08-m-long test fiber. Note that in Fig. 4(b) 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 $181.08 - 4.12 = 176.96$ m of fiber by means of subtracting the two curves in Fig. 4(b) and dividing by the 176.96-m difference in lengths. The red curve in Fig. 1 shows the relative transit time curve, placed on an absolute scale with the value of the delay computed with Eq. (1) from the refractive index at 6700 Å. The choice of using 6700 Å 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 with the calculation and is justified by the small difference between the absolute measurements and calculation. The material dispersion, derived by means of taking the derivative of a curve fit to this data with respect to wavelength, is shown in Fig. 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 UV. The spectrograph setup was the same as for the visible measurements except that the center wavelength was set at 4000 Å.

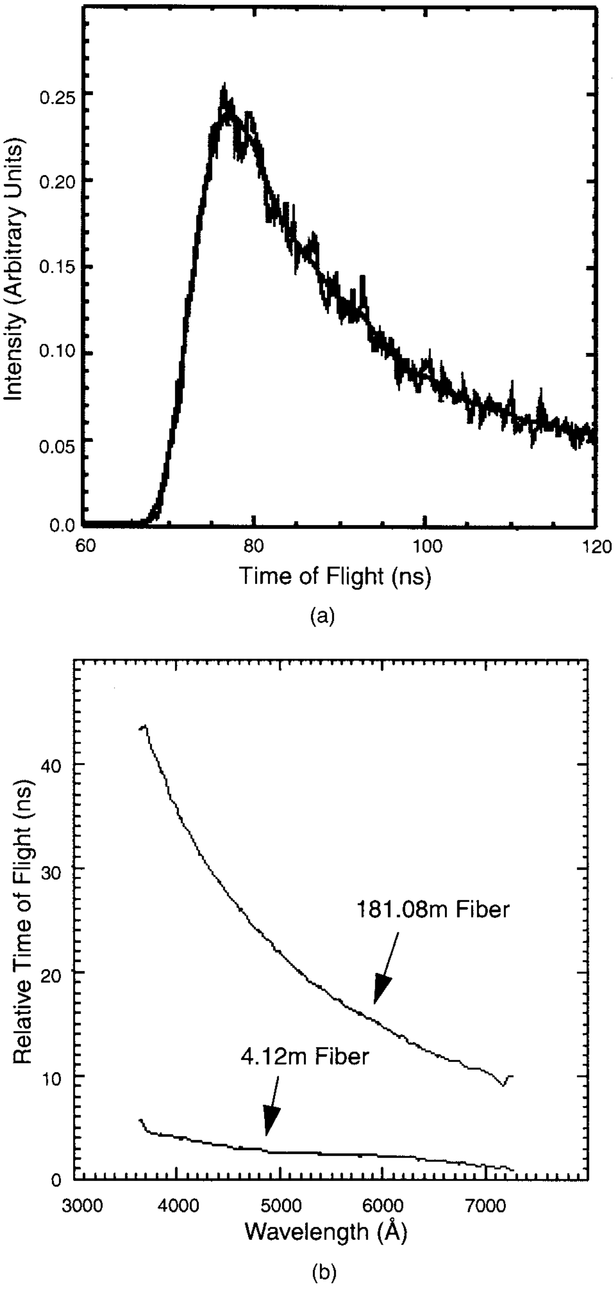

Fig. 4. (a) Lineout averaging over 45-Å interval centered at 5156 Å, from the 181.08-m-long fiber data shown in Fig. 3. The smooth curve is a fast Fourier transform of the data. (b) Relative transit time for two different fiber lengths. The actual distance between the two lines is irrelevant.

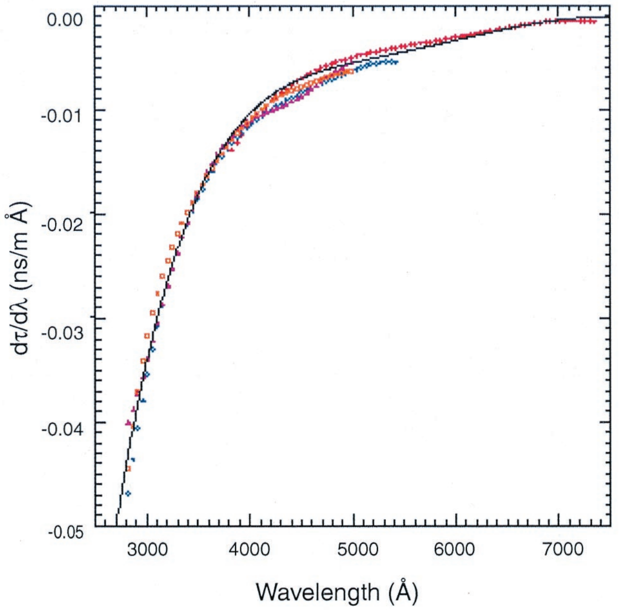

Fig. 5. Material dispersion obtained by differentiation of the curves displayed in Fig. 1. Red is the dispersion of the visible data. Magenta, orange, and blue are the UV data sets, and black is the dispersion of the manufacture's data.

In this mode, data with useful signal intensities were obtained over the 2650–5500-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 defocusing at the other wavelengths. The proximity coupling of the light may mean that 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 0.66, 24.25, and 50.11 m. The relative transit time was determined from the difference between the 50.11- and 24.25-, the 24.25- and 0.66-m-, and the 50.11- 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 4000 Å and displayed in Fig. 1. The material dispersion is shown in Fig. 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, we compare data at each wavelength 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 principle 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, owing to nonideal 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 4000–7200-Å range and ±0.12% averaged over the 2650–5500-Å 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.

3. Attenuation

The time-resolved flash-lamp spectra can also be used to determine the relative fiber attenuation as a function of wavelength. The flash-lamp 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 because of the extra length in the longer fiber.

The attenuation in the fiber is obtained from

$$A(\lambda) = 10 \log_{10}[P_i(\lambda)/P_o(\lambda)]. \tag{4}$$

The wavelength-dependent intensities transmitted through the short and the long fibers are P_i and P_o, respectively. P_i and P_o are measured with two successive flash-lamp pulses on two separate time-resolved spectral images. The first step in our analysis is to derive $A(\lambda)$ ignoring any differences between the injected flash-lamp 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 flash-lamp 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 manufacturer in Refs. 11 and 14. The results are converted into an attenuation per unit length and displayed in Fig. 6.

The amplitude-adjusted experimental data in the visible (3900–7200 Å) agrees with the manufacturer's data to within 9.0%. The UV data below 3800 Å have an average deviation of 7.0%, whereas the UV data above 3800 Å have 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 3800 Å is small enough that a larger difference between fiber lengths is required for accurately measuring it.

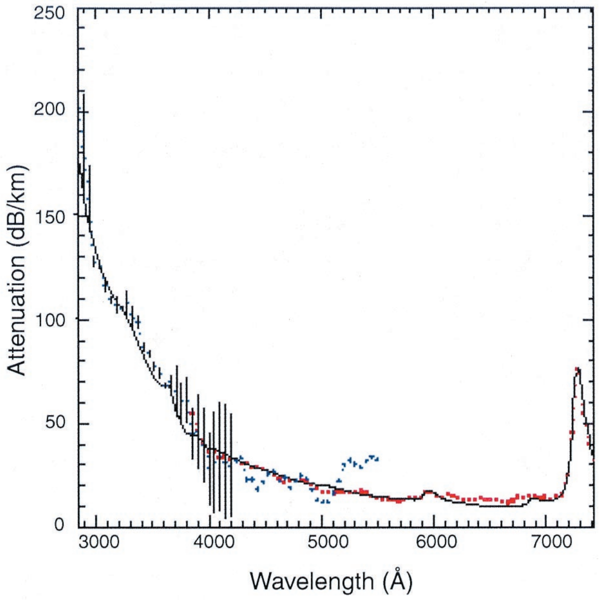

Fig. 6. Experimental and manufacturer's visible light attenuation. Blue is the adjusted UV attenuation, and red is the adjusted visible attenuation. Black is the manufacturer's listed attenuation.

4. Summary

We have presented a new, to our knowledge, 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 means of splitting the light pulse, simultaneously injecting it into a short and a long fiber, and recording the transmitted signal on two separate time-resolved spectrographs.

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