A Comparison of Three Bandwidth Measurement Techniques for Multimode Optical Fibers

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Abstract—This paper presents the results of an experiment intended to compare three distinct methods of measuring the bandwidth of a telecommunication-grade, multimode optical fiber. The three methods are: 1) the time-domain method; 2) the frequency-domain method; and 3) the pulse-spectrum analysis method. We find good agreement between the frequency-domain method and the pulse-spectrum analysis method, but the time-domain method yields results that are lower than the other two for the cases we considered.

I. INTRODUCTION

THE Electronics Industries Association (EIA) currently recommends either of two methods for measuring the bandwidth of telecommunication-grade optical fibers. In the time-domain method, the spectrum of a short pulse that has propagated through the test fiber is compared with the spectrum of a reference pulse (one having traveled through a short reference fiber) via the Fourier transform. The result is the transfer function of the fiber. In the frequency-domain method, a sweep frequency generator drives the light source. The output from the test fiber goes to a spectrum analyzer or a network analyzer, and the fiber transfer function is obtained directly. The input is assumed to be constant during the course of the measurements. These two methods are described fully in the literature [1], [2].

There is a third method, which we will call the pulse spectrum analysis method (PSA), which is not popular in this country, but which is accepted by the International Electrotechnical Commission (IEC). The method can be thought of as a combination of the time-domain and the frequency-domain methods. Both pulses (the reference pulse and the pulse that has propagated through the test fiber) are characterized by a spectrum or network analyzer. We know of no laboratory in this country that uses this method.

In this paper, we will discuss the measurement of fiber bandwidth and make some comparisons between the three methods. Comparative results have been obtained for the three methods at 850 nm and these results will be discussed. In addition, we will discuss the selection of certain measurement parameters. Accuracy and precision can be improved by properly selecting those parameters. Using a computer simulation of the time-domain method, we were able to critically examine the pulse broadening caused by the fiber, using a nonsymmetrical Gaussian-shaped pulse. This term will be used to refer to a pulse which is Gaussian-like on each side of the pulse, but the Gaussian parameters differ on the two sides of the pulse. The simulation includes the effect of a slight reflection that is often seen in the experimental system. The computer-generated pulse closely resembles the pulse seen in practice.

II. THE TIME-DOMAIN METHOD

The measurement parameters set by the operator of a time-domain system include 1) pulse position and time window, 2) time scale setting, and 3) zero-frequency response. In addition to these instrument settings, the operator must deal with the subtraction of the baseline for the measurements. We will discuss this matter first and then turn to the instrument settings.

A. Baseline Subtraction

The signal that appears on the oscilloscope even when the detector input is blocked, is referred to as the baseline signal. This baseline signal will affect the broadened (test) pulse and the reference pulse in different ways. The transfer function is, therefore, skewed unless precautions are taken. In particular, if the pulse being analyzed is weak compared to the baseline signal, the effect will be substantial and the results will not be repeatable unless the effect is subtracted.

Fig. 1 illustrates this effect. Fig. 1(a) shows the input (reference) waveform with and without baseline subtraction. Fig. 1(b) shows the transform of these input pulses. The effect, as seen in the transforms, is illustrated. Fig. 1(c) shows the two transfer functions when the baseline is subtracted and when it is not. Note that 3-dB bandwidth differs by 5.7 MHz (2.3 percent). The last figure shows erratic behavior of the transfer function, a factor that is unsettling to the operator.

Table I provides additional information in this regard. The table lists the statistical results of six measurements on the same fiber with and without baseline subtraction. These measurements were made under conditions of varying sweep time, pulse amplitude, and pulse position on the scope. The results shown in the table, therefore, reflect realistic variations that might be encountered in prac-
Fig. 1. (a) Normalized input waveforms with and without baseline subtraction. (b) The magnitude of the transforms for each case. (c) The magnitude of the transfer function in each case.

These results are particularly telling because they show that the variation encountered with and without baseline subtraction can differ substantially.

B. Pulse Position and Time Window

The time-domain method uses the discrete Fourier transform and, therefore, conflicting needs are encountered. The operator must choose carefully between reasonable frequency resolution and the need to avoid aliasing [3]. If one could use any number of data points, the conflict would not arise. In practice, this is not feasible. The errors caused by finite frequency resolution are not difficult to estimate, but aliasing is less tractable. It is difficult to know just how and when aliasing becomes a fac-
The relationship between the variation of the spread in measurements and the square root of the product of number of data points encompassed in the input and output waveforms.

The magnitude of the Fourier transform is the vector sum of contributions from frequencies on both sides of the folding frequency (1/2 T, where T is the time between data points). Thus the only method of determining with certainty whether or not aliasing is skewing the transform is to determine the transform magnitude at the folding frequency. If it is not very nearly zero, the results are not reliable. In practice, the operator positions the pulse more or less in the middle portion of the time window, usually in a random fashion. The position of the pulse in the time window determines the phase of the Fourier transform. Thus the random positioning of the pulse in a series of measurements yields random phase values and the resultant transform magnitude changes accordingly. Aliasing will manifest itself in the standard deviation or spread in the measured bandwidth.

For the computer experiment, we hypothesize that a candidate rule is based on the number of data points in the "effective duration" of the pulse. The effective duration is the full duration at the 0.1 percent of maximum point at full scale on a three digit digital volt meter (DVM). This effective duration is the duration referred to in Table II and Fig. 2

<table>
<thead>
<tr>
<th>3 dB Bandwidth (MHz)</th>
<th>247.9</th>
<th>243.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Deviation (MHz)</td>
<td>3.8</td>
<td>11.4</td>
</tr>
</tbody>
</table>

If the pulse is reasonably well-behaved (which is usually the case in fiber systems), it seems intuitive that the number of such data points should be a reliable indicator of whether or not aliasing is a factor.

We tested this hypothesis by computer simulation, using a pulse shape similar to what is frequently seen in fiber systems: a nonsymmetrical pulse with Gaussian characteristics on both sides of the maximum. The simulation used an ideal (perfect) pulse of that character, the exact transform for which is known. In this simulation, the computer allowed precise positioning of the pulse in the time window. The pulse duration, sweep time, number of data points, and pulse position could thus be adjusted to simulate the experiment. The computer simulation calculated the 3-dB bandwidth using the usual time-domain methods. The transform of the input and output pulses were taken and the ratio provided the transfer function, which in turn yielded the bandwidth.

The results of this computer experiment are given in Table II and Fig. 2. In Table II, n(I), n(O), and σ are, respectively, the number of data points in the effective duration of the input pulse, the number of data points in the effective duration of the output pulse, and the standard deviation of the results (megahertz) based on eleven runs. The reader will note the correlation of n(I) and n(O) with σ. N is the total number of data points in the time window. T_in and T_out are the effective durations of the input and output pulses.

In Fig. 2, we plot the error as a function of the square root of the product of the number nonzero data points. Sampled data are rounded in the simulation, to the accuracy of the digital voltmeter. Intuitively, it seems that both input and output pulses are important to precision. The relationship shown in Fig. 2 indicates that the number of nonzero data points plays a crucial role in the precision.

Table II gives the number of sampling points encompassed by the pulse. It is obvious that the error is dependent on the number of such points and that the error decreases with an increase in the number of such sampling points. The worst case always corresponds to approxi-
TABLE II
VARIATION OF BANDWIDTH AND STANDARD DEVIATION OF BANDWIDTH
(BOTH IN MEGAHERTZ) FOR ELEVEN COMPUTER-SIMULATED
MEASUREMENTS WITH RANDOM PULSE POSITION.

<table>
<thead>
<tr>
<th>Time Window/N</th>
<th>100ns/256</th>
<th>50ns/256</th>
<th>50ns/512</th>
<th>20ns/256</th>
<th>50ns/1024</th>
<th>20ns/512</th>
<th>20ns/1024</th>
<th>10ns/1024</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01ns</td>
<td>2.127</td>
<td>0.199</td>
<td>0.010</td>
<td>0.008</td>
<td>0.000</td>
<td>0.001</td>
<td>0.048</td>
<td>0.009</td>
</tr>
<tr>
<td>n(1)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
<td>0.8</td>
<td>1.0</td>
<td>2.1.</td>
<td>4.2</td>
</tr>
<tr>
<td>n(0)</td>
<td>10.1</td>
<td>20.2</td>
<td>40.5</td>
<td>50.6</td>
<td>81.0</td>
<td>101.2</td>
<td>202.4</td>
<td>404.8</td>
</tr>
<tr>
<td>0.05ns</td>
<td>2.276</td>
<td>0.146</td>
<td>0.552</td>
<td>0.614</td>
<td>0.185</td>
<td>0.070</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>n(1)</td>
<td>0.5</td>
<td>1.0</td>
<td>2.1</td>
<td>2.6</td>
<td>4.2</td>
<td>5.2</td>
<td>10.4</td>
<td>20.9</td>
</tr>
<tr>
<td>n(0)</td>
<td>10.1</td>
<td>20.2</td>
<td>40.5</td>
<td>50.6</td>
<td>81.0</td>
<td>101.2</td>
<td>202.4</td>
<td>203.4</td>
</tr>
<tr>
<td>0.1ns</td>
<td>6.667</td>
<td>3.966</td>
<td>0.735</td>
<td>0.120</td>
<td>0.038</td>
<td>0.013</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>n(1)</td>
<td>1.0</td>
<td>2.1</td>
<td>4.2</td>
<td>5.2</td>
<td>8.3</td>
<td>10.4</td>
<td>20.9</td>
<td>20.9</td>
</tr>
<tr>
<td>n(0)</td>
<td>10.2</td>
<td>20.3</td>
<td>40.7</td>
<td>50.9</td>
<td>81.0</td>
<td>101.7</td>
<td>203.4</td>
<td>208.7</td>
</tr>
<tr>
<td>0.25ns</td>
<td>19.05</td>
<td>2.121</td>
<td>0.070</td>
<td>0.002</td>
<td>0.004</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>n(1)</td>
<td>2.6</td>
<td>5.2</td>
<td>10.4</td>
<td>13.0</td>
<td>20.9</td>
<td>26.1</td>
<td>52.2</td>
<td>52.2</td>
</tr>
<tr>
<td>n(0)</td>
<td>10.4</td>
<td>20.9</td>
<td>41.7</td>
<td>52.2</td>
<td>83.5</td>
<td>104.3</td>
<td>208.7</td>
<td>208.7</td>
</tr>
<tr>
<td>1ns</td>
<td>9.999</td>
<td>0.205</td>
<td>0.003</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>n(1)</td>
<td>10.4</td>
<td>20.9</td>
<td>41.7</td>
<td>52.2</td>
<td>83.5</td>
<td>104.3</td>
<td>208.7</td>
<td>208.7</td>
</tr>
<tr>
<td>n(0)</td>
<td>14.9</td>
<td>29.8</td>
<td>59.7</td>
<td>74.6</td>
<td>119.4</td>
<td>149.2</td>
<td>296.8</td>
<td>296.8</td>
</tr>
</tbody>
</table>

approximately two sampling points being encompassed by the input pulse. In that case, there will be times when one data point is encompassed and other times when two are encompassed, depending on pulse position. Since a single nonzero data point corresponds to the delta function, we expect a significant difference between this case and the case when two nonzero points are encountered in the input pulse. The output pulse always had ten or more points in the cases we examined. The number of such points depends on the fiber bandwidth.

When two sampling points are encountered in the input pulse in each of two different measurements, there may be a significant difference between the two results. This is seen as follows (cf. Fig. 3). Consider a waveform \( g(t) \) and its discrete Fourier transform, given as follows [3]:

\[
G(n/NT) = \sum_{k=0}^{N-1} g(kT) \exp(-j2\pi nk/N) \quad (1)
\]

with \( n = 0, 1, 2, 3, \ldots N/2 - 1 \) where \( N \) is the total number of data points, \( k \) is the order of waveform data points, \( T \) is the time between data points, and \( n \) is the order of discrete frequency components of the Fourier transform. Assume that only the \( m \)th and the \( (m+1) \)th data points are nonzero, as shown in Fig. 3. Assume further that the data points are positioned differently on the pulse, as shown in the figure. In particular, the two cases considered in the figure are for \( g(mT) = g[(m+1)T] \)

\[ G(n/NT) = g(mT) + g[(m+1)T] \]

and \( g(mT) = g((m+1)T) \). We have [3]

\[
G \left( \frac{n}{NT} \right) = [g^2(mT) + g^2((m+1)T)] + 2g(mT)g((m+1)T) \cos \left( \frac{2\pi n}{N} \right) \right]^{1/2}
\]

and

\[
G(0) = g(mT) + g((m+1)T)
\]
\[ G \left( \frac{1}{2T} \right) = g(mT) - g((m + 1)T). \]

Fig. 3 illustrates the difference in the two cases. The results are independent of pulse shape. This is an example of how the change of phase affects the magnitude of the Fourier transform when aliasing is present.

Table II indicates that in some cases, the number of sampling points is less than one. Actually, either one or no sampling points are encountered. The Fourier transform is the same in each of these cases (a flat line); hence, the difference between this case and most of the others. We simulated this case by letting the input pulse duration be 0.01 ns (cf. Table II).

The results given in Table II and Fig. 2 are intended only to be a guide for the operator, based on the ideal pulse that we examined. We believe that the guide, based on these data, is useful in most optical fiber systems because the pulses encountered are reasonably well behaved and they have the general shape of the simulation pulse. In the final analysis, however, the presence or absence of aliasing can be determined with certainty, only by examining conditions near the folding frequency.

C. Time Scale Setting and Fluctuation

The operator is obliged to set the terminal points of the time window scale of the sampling oscilloscope before beginning the time-domain measurements. This is obviously done separately for the pulses out of the reference and the test fiber. Even a small difference in these two scale settings will lead to a noticeable difference in the results. The reason for the error is quite intuitive: the setting affects the pulse duration seen by the computer. Fig. 4 shows the resulting error as a function of scale-setting difference between the reference and the test fibers.

A secondary effect of the difference in scale setting is a fluctuation in the measured response. The reference and the test pulse Fourier transforms sometimes show fluctuations that do not appear on the transfer function. These fluctuations may be due to reflections, interference, or the discontinuity due to the truncation of the signal in the time window. A reflection is usually at a fixed position with respect to the pulse peak and its magnitude is proportional to the pulse magnitude; it may also have the same shape as the pulse. If the scale setting is perfect, then the two Fourier transforms will have fluctuations, but the transfer function will be smooth. Baseline noise is an example of noise that can cause fluctuation that is not canceled in the transfer function. Fig. 1(c) is an example. Baseline subtraction will usually eliminate the effect.

We have used the perfect asymmetrical pulse, described earlier, to simulate the problems associated with these fluctuations. Fig. 5 shows the transfer function for the same simulated reference and test pulse with reflections for a 1- and 2-percent error in setting the time window. Figs. 5(a), (b), and (c) indicate the nature of the degradation with error in scale setting.

Fluctuation in the transfer function will deteriorate the repeatability of the measurements. Fig. 6 gives the 3-dB bandwidth shift due to fluctuation as a function of a time-window setting error. The lower straight line in the figure is the same as the one in Fig. 4.

Another cause of fluctuation in the transfer function is the random error in the sweep driving circuit. The effect is often small with respect to that of time-window error. Fig. 7 shows the transfer function for a sample case chosen from the worst of ten simulations. The maximum random error in the sweep driving circuit for this case is 20 ps.

D. Zero-Frequency Response Determination

The zero-frequency response is frequently taken as the same as the response at the first nonzero frequency point. The selection is important because, in fact, the 3-dB bandwidth is referenced to the zero-frequency response. If the resolution is poor, the error is critically dependent on the manner in which the zero-frequency response is chosen. Fluctuation in the transfer function will further complicate the matter.

We find that a curve-fitting routine provides a suitable solution to this problem. We fit the data for frequencies less than about 200 MHz to a second-degree polynomial and extend the curve to zero frequency. We find that a second-degree curve is adequate for the cases we have encountered. Additional refinement is probably not necessary. Table III gives the results.

III. PULSE-SPECTRUM ANALYSIS

The Pulse-Spectrum Analysis (PSA) method is a combination of the frequency-domain and the time-domain methods. Many of the equipment considerations are, therefore, the same as in the other systems. In this technique, a pulse generator drives the laser diode to produce a series of pulses which is injected into the mode scrambler and then into the fiber. The detected output goes to the spectrum analyzer, where the frequency components are evaluated. A block diagram of the system is shown in Fig. 8.

There are two problems that deserve mention. The first evolves from the task of "finding" the peaks of the spectral lines as the analyzer sweeps through the frequency range of interest. The second involves the selection of operational parameters in view of various conflicting requirements. The latter problem will be discussed first.

The signal to noise ratio required by the spectrum ana-
Fig. 5. (a) Magnitude of the transfer function (simulated) when there is no scale offset error. (b) A 1-percent error. (c) A 2-percent error.

Fig. 6. Relationship between the 3-dB frequency error and scale offset error, with and without fluctuations in the transfer function.

Fig. 7. Magnitude of the transfer function (simulated) illustrating the fluctuation that can occur due to a random error in the time-sweep driving voltage.

In the PSA method, the pulse train is decomposed into frequency components and the fiber characteristics are determined from the relative amplitudes of the spectral lines.
The bandwidth of the spectrum analyzer determines the duration of each of the spectral lines. The envelope of the series of spectral lines is the response of interest. Because there are a finite number of spectral lines, the operator must ensure that data are taken at or near the center of every spectral line, while minimizing the time required to take the data. The computer that drives the experiment controls the steps between data points and the search in a way that offers a suitable compromise in this regard. Because the step size is finite, it is quite probable that the data points will not coincide exactly with the peak of every spectral line. As a result, one usually encounters an "offpeak error." The largest step that can be taken in the frequency domain is estimated by assuming that the IF filter of the spectrum analyzer is an LC filter. The error encountered because the peak is not encountered (the off-peak error) when the bandwidth (B) of the spectrum analyzer is 300 kHz, is found from

\[ E_{\text{off}} = 20 \log \left\{ 1 + \left( \frac{2B}{f} \right)^2 \right\} \]  

(5)

where \( \Delta f \) is the difference between the frequency at which the data is taken and the frequency of the spectral line. The step size is then dictated by the allowable error. Table IV shows some estimates.

By selecting a step size of 40 kHz (\( \Delta f = 20 \) kHz), for example, the maximum error will be 0.08 dB. Fig. 9 shows the results of an experiment designed to determine the repeatability of the measurements. The 40-kHz step size was used. The curve is obtained by taking data twice, under exactly the same conditions. The inherent error in the system is the error due to the uncertainty in locating the peak. This error could be reduced by increasing the time required to take the data. The process is one of reinterest.

The error discussed here is manifested as a nonuniformity in the trace of Fig. 9. The figure also shows, for comparison, the results of a repeatability test for the frequency-domain method.

The error in decibels can be converted to error in locating the 3-dB bandwidth by noting the slope of the transfer function near the 3-dB bandwidth. We have estimated it to be about 50 MHz/dB. The error of 0.08 dB then corresponds to about 4 MHz. Measurement time is also influenced by the linearity of the relationship between the programmable drive voltage and frequency. Be-
cause of nonlinearity, there is uncertainty in the frequency at which the search for the peak begins. Thus one must allow for a comfortable search range after each step; 400 kHz is typical in the system used here. Decreasing this range will decrease the time required for the search, but it does so at the risk of missing one or more of the spectral peaks.

B. Bandwidth Comparisons

We have measured the bandwidth of a multimode graded-index fiber at 850 nm using the time domain, the frequency domain, and the PSA methods. The results are shown in Table V, which contains two sets of data. For the data in the top part of the table, the test fiber was placed in the system and frequency-domain data, time-domain data, and PSA data were taken. The reference fiber was then placed in the system and without disturbing the fiber between measurements, data were taken for each of the three methods. This procedure was followed three times (corresponding to the numbers 1, 2, and 3 in column 1 of the table) to yield the data in the top part of the table. Thus the top part of the table gives results for three runs when the launch conditions are identical; the data thus allows a direct comparison of the three methods without having to account for possible effects of the launch conditions.

In the second experiment, for which results are given in the lower part of Table V, the reference and the test fibers were cleaved and reinserted in the system for each of nine experiments. The statistical results are given in the table.

The time-domain parameters used in this experiment were the following: 50-ns time window; 512 data points; and the input pulse width was about 0.5 ns. The time-domain method yields a value of a 3-dB bandwidth that is slightly lower than the value obtained using the other two methods. We have noted a degree of consistency in this fact, even beyond the data that are reported here. There is also consistent and very good agreement between the frequency domain and the PSA methods. The PSA method thus lends credence to the veracity of the other two methods.

IV. Conclusions

The PSA method has the advantage of being simple to use and requiring only a minimum of equipment. The method allows the operator to adjust operational parameters in an intuitive and meaningful way. If time is not important, he can adjust the pulse repetition rate and search time to accommodate the required frequency resolution and minimize the off-peak error. This error is thought to induce the fundamental limit to the precision of the method. The choice of pulse duration also affects the signal-to-noise ratio. About 20 min were required to determine the bandwidth using the PSA method in our case. That is considerably more than the 2 min typical for the frequency-domain method.

The frequency-domain method has the advantage of offering good signal-to-noise ratio and good repeatability. Resolution can be increased to about 1 MHz by increasing the measurement time to about 10 min.

The frequency-domain method has the advantage of offering good signal-to-noise ratio and good repeatability. Resolution can be increased to about 1 MHz by increasing the measurement time to about 10 min.

The time-domain method is time consuming, due primarily to the calculations that are required. It has the advantage of requiring relatively unsophisticated equipment; phase information can be obtained, if needed. The pulse repetition rate can be as low as several kilohertz.

The rather high-standard deviation for the time-domain data shown in Table V may indicate that aliasing was present. In theory, there is no fundamental reason for time-domain data to be worse than frequency or PSA data.

Phase information is not available in the frequency domain method or the PSA method unless sophisticated equipment is used (e.g., a complex network analyzer or vector voltmeter).

Acknowledgment

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V. References