Optical Fiber Metrology

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Invited Paper

***Abstract*—The development of metrology to support the optical fiber communications industry is an excellent case study of how stakeholders—fiber manufacturers, their customers, standards-developing organizations, and (in the U.S.) the Federal Government—worked together to develop product specification standards that facilitated the growth of an industry. This paper reviews some of that history, primarily from the perspective of the National Institute of Standards and Technology, which worked with the industry to provide independent research and neutral coordination of many industry studies and measurement comparisons.**

***Index Terms*—Instrumentation, measurements, multimode fiber, optical fiber metrology, single-mode fiber, standards.**

I. Introduction

FROM the 1966 publication of an analysis concluding that optical fiber could be a viable communications medium [1], through the key experimental achievements [2][1] to the earliest systems carrying commercial telephone calls in 1977,[2] little attention seems to have been given to how an optical fiber could be accurately specified and characterized. The difficulties in fiber metrology that would emerge and complicate the market for fiber as a large volume commodity seem to have been generally unanticipated or underestimated.

Though the first "low loss" fiber [4] was a single-mode fiber, for the next decade or more, attention shifted to highly multimode fiber. It could be used with light emitting diodes as well as lasers, which allowed greater dimensional tolerances. And, with the advent of graded-index designs [5], it offered the possibility of transmitting at what were then considered to be very high data rates. The idea of grading the refractive index of the core to equalize the group velocities of the modes was a very important innovation but, at the time, it was difficult to fully equalize the group velocities. Further, it emerged that, in most multimode fiber, mode groups suffered different attenuation, and the coupling of power between modes could be substantial. Differential attenuation results in a length-dependent power distribution among the modes, and mode coupling often results in unanticipated equalization of group velocities. The net result is that the measurement of transmission properties typically depends on how light is launched into a multimode fiber. Both attenuation and bandwidth are nonlinear with fiber length. And the transmission properties of two or more fibers spliced together are often unpredictable from measurements on the individual pieces.

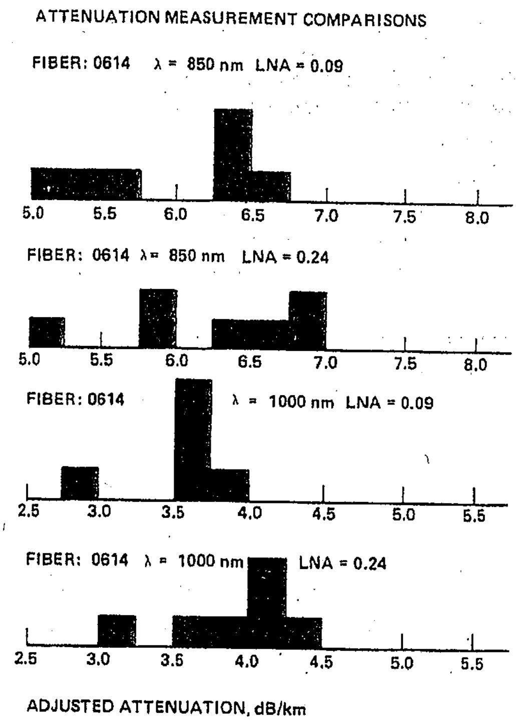

Fig. 1. Histogram of the results of a 1979 interlaboratory comparison of multimode fiber attenuation measurements. [6].

By the late 1970s, these problems were fully apparent. At the time there were at least seven manufacturers of optical fiber in the U.S. that were selling multimode fiber with attenuation of a few decibels per kilometer in the wavelength ranges then of interest, around 850 and 1300 nm. However, a comparison of attenuation measurements among those manufacturers[3] [6] showed that measurements by different companies on the same

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[1] For good surveys of the technology as of 1975, see two conference proceedings: Optical Fiber Transmission, 1995, Williamsburg, Optical Society of America/IEEE (the first of the series of conferences that became known as the Optical Fiber Communications Conference, OFC) and Optical Fibre Communications, IEE, London, 1975 (the Proceedings of the First European Conference on Optical Communications, ECOC)

[2] At least three systems carrying commercial traffic became operational in 1977: a system in Chicago installed by AT&T (Illinois Bell), a system near Long Beach, CA, installed by GTE, and a system near Martlesham Heath, U.K., installed by the British Post Office. For details, see, for example, [3].

[3] Participants were Corning Glass Works,Galileo Electro-Optics Corp., ITT Electro-Optical Products, Optelecom, Inc., Valtec Corp., Times Fiber Communications, and Western Electric. This was the first of nearly 30 comparisons of optical fiber measurements among industry laboratories that were overseen by NIST and used to document measurement problems and validate standard procedures.

fiber could vary by a substantial fraction of the average of all the participants (Fig. 1). Similar disagreements occurred with bandwidth measurements and, perhaps to a lesser extent, with the determination of a variety of other fiber parameters, both optical and physical. (Early work on multimode fiber is discussed in more detail in Section II.)

Inconsistent specifications had become a major impediment to market development and that, coupled with the fact that around 20% of production costs were being devoted to measurements, led manufacturers and their customers to search for standardized specifications and measurement techniques. After one or two false starts, most U.S. manufacturers and many of their customers began to work on voluntary standards with the coordination of the Electronics Industry Associations (EIA), and later with its affiliate, the Telecommunications Industry Association (TIA). Over the years, these organizations have produced many standard specifications and hundreds of test procedures that were adopted voluntarily by U.S. fiber manufacturers. Most were also submitted as U.S. recommendations to international standards groups, the International Electrotechnical Commission (IEC), the International Organization for Standards (ISO), and the International Telecommunications Union (ITU), and many were adopted as international standards (Section III).

In this same period, the late 1970s, the optical equivalent of time-domain reflectometry [7] (OTDR) arose as a method of determining characteristics along the length of a fiber. While OTDR has rarely been considered the most accurate method for determining fiber properties, its enormous diagnostic power has made it an essential tool in systems engineering, and one of the most commercially successful instruments in optical communications (Section IV).

When single-mode fibers began to dominate the field in the mid-1980s, much of the work done on multimode fibers (Section II) applied directly or indirectly. One major unsolved problem, bandwidth measurements in multimode fiber, became unimportant. It returned a decade later, though, when work to extend Ethernet standards to 1 Gb/s and then 10 Gb/s renewed the market for multimode fiber (Section V). Ultimately, the problem was solved more by improvements in the fiber than by better measurements.

Further reductions in fiber loss, including the near elimination of absorption by OH, shifted attention to the 1550-nm region of the spectrum where fiber with attenuation less than 0.2 dB/km became readily available. And, with improved understanding and control of waveguide dispersion, it became possible to produce fibers in which the minimum dispersion was shifted from 1300 to 1550 nm (or otherwise tailored over this region). The 1550-nm spectral region became the focus for long-distance systems. Data rates increased rapidly, with systems moving from 2.5 Gb/s, to 10 Gb/s, and then 40 Gb/s. As they did, dispersion caused by the difference in group velocity of different polarization states [polarization mode dispersion (PMD)] became an additional problem. For metrologists, these developments meant new problems in radiometry, in accurate chromatic dispersion measurements, and in the new area of PMD measurements, all in a region where high quality instruments were not yet readily available (Section VI).

Then the development of the Erbium-doped optical fiber amplifier (EDFA), which enabled wavelength-division multiplexing, revolutionized long-distance optical communications. Total data transmission rates in demonstration ("hero") experiments rose quickly through 1 Tb/s to more than 10 Tb/s in systems that sometimes employed hundreds of optical frequencies separated by as little as 25 GHz. Simple, accurate methods of wavelength measurement in spectral regions of interest became a major thrust of metrology laboratories (Section VII).

The remainder of this paper describes the history outlined above in more detail, largely from a perspective of work at the National Institute of Standards and Technology (NIST) where, in 1976, the authors, along with Bruce Danielson, started a research program on fiber metrology that continues to be active. NIST was then known as the National Bureau of Standards (NBS). Its Boulder Laboratories had, since the early 1960s, maintained the U.S. National Standards for laser radiometry and microwave metrology, and were active in a variety of other measurement fields, such as laser frequency metrology and time-domain measurements, that provided a solid base from which to launch work on fiber metrology.

II. Early Multimode Fiber Measurements

In the early multimode fiber used for telecommunications, the refractive index decreased approximately parabolically from the center of the core to the cladding. Core sizes in the range of 50 to 70 μm and numerical apertures of 0.2 to 0.3 resulted in hundreds of allowable waveguide modes. While the index profile in such a fiber is designed to equalize group velocity, the equalization is imperfect: group velocity and attenuation vary slightly among mode groups. Measurement results for attenuation and bandwidth therefore depend on the spatial and angular distribution of light launched into the fiber.

The most accurate technique for measuring attenuation is the "cut-back" method. Here, light is launched into the long test fiber, and the power exiting the output end is measured. Without disturbing the launched power, the fiber is cut about 2 m from the input, and the power exiting this short length is measured. Attenuation is determined from the ratio of powers, and dividing by fiber length gives the attenuation rate.

The first measurements of differential mode attenuation were made by independently resolving the spatial and angular light distribution exiting the fiber [8]. The usual situation is for the higher order modes (those with large radial and angular extent) to exhibit more attenuation than the mid-order modes. Power launched into higher order modes will therefore decay more quickly with length.

The proper launching conditions for attenuation measurements were one of the first problems addressed by standards groups. The attenuation was to be measured in a manner that would allow the attenuation of individual fibers in a link to be added linearly to predict the overall link loss. This means launching light to achieve what was termed an "equilibrium mode distribution" (EMD) at the input to the fiber under test [9].

The means of approximating the EMD launch was somewhat controversial within the EIA. One method, proposed by Corning, was referred to as the "limited phase space" (LPS)

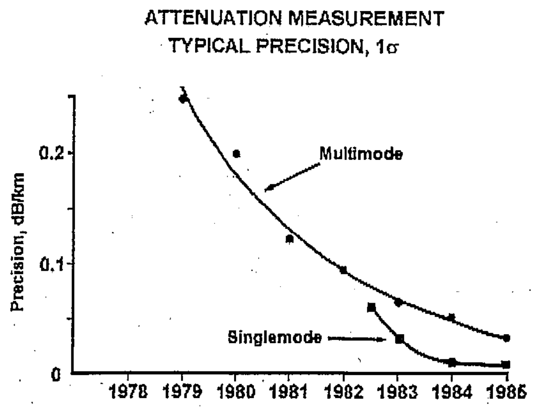

Fig. 2. Improvement in single test set precision for optical fiber attenuation measurements as standards were developed.

launch. This launch was also called the "beam optics" or "70/70" launch. Lenses and apertures were used to create a spot of light having a diameter equal to 70% of the fiber core diameter. The launch angle was independently adjusted to be 70% of the fiber numerical aperture. Additional optics were provided to center the spot on the core of the fiber under test.

Another method, proposed by AT&T Bell Laboratories, was referred to as the "mode filter" launch [10] or sometimes the "mandrel wrap." In this technique, the fiber under test is excited with an "overfilled" launch in which the launch spot greatly exceeds the core diameter and the launch cone greatly exceeds the numerical aperture of the fiber. The far-field radiation pattern exiting the long test fiber is measured. This pattern is indicative of that of the EMD, since power that was in the higher order modes is greatly reduced through propagation. A short length (typically 2 m) of the test fiber is overfilled and a mode filter is applied to replicate the previous far-field pattern. This procedure "qualifies" the mode filter for use on the test fiber. The measurement then requires overfilling the test fiber and applying the mode filter to the input end before its cut-back point. The specific type of mode filter is not specified, but practical experience indicates that a few wraps of the fiber around a round rod (mandrel) of some experimentally determined diameter is sufficient.

At that time, it was also very important to remove cladding light, which could be significant in the short, typically 2 m, lengths used in the cut-back method and which could lead to substantial errors. This was typically done using index matching liquid on a bare section of fiber. Later the problem of cladding light diminished when most manufacturers began to use coatings with higher refractive indices.

NIST performed an interlaboratory comparison to evaluate the effectiveness of the two launches. A standard deviation of 0.23 dB/km (average over all test fibers) was achieved with no significant difference observed between the two launches [11]. With the development of standards and greater experience, uncertainties in the measurement of attenuation continued to decline. Fig. 2 is a chart showing improvement in the precision of attenuation measurements at one major company.

Bandwidth measurements on multimode fibers were even more problematic. This was caused by the extreme sensitivity of the bandwidth to slight perturbations in the refractive index profile. For example, a sinusoidal distortion of 1% in the profile could reduce a theoretical bandwidth of 8 GHz/km to 200MHz/km [12].

Predicting the bandwidth of several concatenated fibers was particularly difficult. In some fibers, higher order modes might exhibit more delay than lower order modes. If such fiber is joined to another fiber with opposite behavior, i.e., lower order modes having greater delay, compensation can result, and the bandwidth of the joined fibers could be higher than either fiber alone.

Differential mode delay (DMD) measurements on fibers with little mode coupling showed that the DMD for joined fibers is simply the arithmetic sum of the individual fiber DMDs [13]. As the industry matured, fiber length uniformity improved and this, along with improved cable design, resulted in reduced mode coupling. Thus, compensation issues remained important, and the prediction of concatenated performance was unresolved.

It would seem natural for bandwidth to be determined using the same launching conditions used for attenuation measurements. Some early measurements showed that restricted launching did not really improve the bandwidth prediction for concatenated fibers [14]. Standards groups instead chose an overfilled launching condition for bandwidth. The overfilled launch was easier to achieve experimentally, and it was hoped that it would reduce the systematic bias between laboratories.

Most early bandwidth measurements were performed with pulsed laser sources typically driven by an avalanche transistor and a low impedance charge line [15]. Unlike the incoherent sources used in attenuation measurements, the short pulse lasers exhibited speckle and irregular radiation characteristics that often varied with time during the pulse. Thus, even achieving a reliable overfilled launch was challenging.

Typically the solution was to use a "mode-scrambler," usually a short length of fiber modified in some way so that the radiation profile at the output approximated an overfilled launch, regardless of the spatial distribution at the input. Several creative versions were reported including a fiber covered by ball bearings which created both micro- and macrobending. Perhaps the two most popular mode scramblers were the step-graded-step (SGS) fiber and a step fiber with serpentine macrobends [16]. The SGS mode scrambler consisted of a graded index fiber, 1 m long, fusion spliced between 1-m lengths of step index fiber [17].

The fiber bandwidth was defined in the frequency domain as that frequency where the frequency response (in optical power) decreased by 3 dB with respect to zero frequency. In very early fiber work, bandwidth was sometimes specified by measuring pulse broadening at the full-width at half-maximum (FWHM) points and calculating the bandwidth based on a Gaussian model. But the fiber-broadened pulses often were not Gaussian, and this method was shown to lead to errors of up to 70%, when compared to the 3-dB bandwidth using the ratio of the Fourier transforms of the output and input pulses. [18].

Interlaboratory round robins to determine fiber bandwidth using procedures drafted by the TIA yielded overall one standard deviation agreement of 12% on fibers having 3-dB bandwidths of 214–418 MHz. This was typical agreement at the time, but fibers were occasionally found that exhibited more disagreement. These were termed "rogue" fibers by some in the standards groups. Further inspection found these fibers to have steep

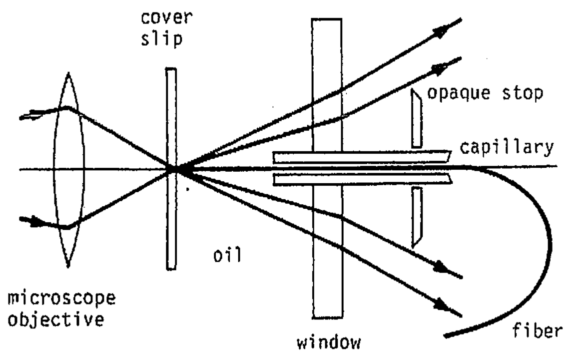

Fig. 3. Diagram of Refracted Near-Field apparatus.

dips in the frequency response near the 3-dB frequency. Consequently, a small change in launching conditions could produce a large change in the 3-dB frequency. The solution was to obtain a best fit Gaussian to a large portion of the frequency response and obtain the 3-dB bandwidth from the fitted curve, averaging out ripples or dips in the frequency response.

Bandwidth was also measured directly in the frequency domain. This was accomplished by using a continous-wave (CW) laser diode source modulated at radio-frequency (RF) frequencies [19]. A swept frequency oscillator and a spectrum analyzer were used to directly acquire the frequency response. Comparisons between time- and frequency-domain techniques yielded good agreement [20], [21]. The two methods can therefore be used interchangeably.

In early multimode fibers, the attenuation and bandwidth were clearly the most important measurements. Fiber pricing schedules were based on performance levels for these parameters, with lower attenuation and higher bandwidth fibers receiving premium prices. The other parameters specified and measured in quality control include core diameter, cladding diameter, and numerical aperture. While these were important, they did not require extremely small tolerances.

Core diameter and numerical aperture were defined from the fiber refractive index profile. Since this was a recommendation of international standards groups (mainly the IEC), the US national standards body (TIA) felt obliged to accept this basic definition. Index profile measurements were difficult to perform but were needed for quality control. The most basic method for index profile was the "slab method." A thin transverse slab of the test fiber was cut and polished. The slab was placed in an interference microscope, and the resulting fringe pattern was acquired. An analysis of this pattern yielded the index profile. Sample preparation was tedious, and fibers could be measured at the rate of about one per day [12]. A significant improvement was the transverse interference method, in which the fiber was immersed in index matching fluid and examined transversely in an interference microscope [12], [22]. Assuming cylindrical symmetry, the profile can be computed from the interferogram. Sample preparation is trivial, and results are rapidly obtained. Disadvantages include the assumption of symmetry, poor resolution near the axis, and the expense of the microscope.

Many laboratories were interested in a more cost effective method, and began to use a technique known as the refracted near-field method (sometimes also known as the refracted ray method) for determining index profile (Fig. 3). This very clever procedure was based on scanning the entrance face of the fiber with the vertex of a high numerical aperture cone of light and measuring the change in the amount of refracted (unguided) light [23]–[25]. The source was typically a HeNe laser focused to a very small spot, providing submicrometer resolution. Commercial instrumentation became available, and the technique, though not amenable to rapid quality control measurements, became one of the most widely used methods for laboratory work on both multimode and single-mode fibers.

An alternative method for determining core diameter and numerical aperture uses the near- and far-field radiation patterns from the output end-face of a short length of fiber (typically 2 m). If the input end of a near-parabolic profile graded-index fiber is uniformly illuminated with incoherent light that overfills the fiber core and numerical aperture, the output near-field pattern will approximate the index profile [26], [27] and the angular extent of the far-field pattern gives the numerical aperture through the expression $NA = \sin\theta_5$, where θ_5 is the half-angle where the intensity has decreased to 5% of the maximum value Generally both patterns are nearly circularly symmetric, so that a single scan through the center suffices. It should be emphasized that this does not apply to step-index fibers whose near-field patterns are greatly influenced by leaky modes.

III. From Measurement Research to Measurement Standards

The process through which standards for core diameter and numerical aperture emerged from research on measurement techniques is a good illustration of how the TIA approached the problem of useful standards, and set the stage for many other standards developed later. Laboratories submitted the test method they preferred for a particular fiber parameter. Rather than rejecting methods through a ballot process, the TIA (Committee P6.6) attempted to reconcile different approaches through round-robin testing and the adjustment of procedural details so various approaches would give sufficient agreement. In one preliminary study, "core diameter by the transmitted near-field (TNF) method" was defined as that diameter where the TNF intensity dropped to 5% of the maximum value. An interlaboratory round robin using six 50-μm core fibers produced an overall standard deviation of 0.5 μm [28]. Core diameter obtained from index profile measurements by the transverse interferometry method, on smooth profile fibers, agreed within 1 μm. On fibers with structure in the index profile near the core-cladding boundary, the agreement was not as good. Further studies and comparisons by the TIA found that a core diameter based on the 2.5% intensity points on the near-field would minimize disagreement between the TNF and index profile methods [29]. Also, curve fitting could be employed to smooth structure in the index profile with diameter being determined from the curve fit. These modifications were adopted into the final test procedure to provide an acceptable measure of core diameter, that has been used by the industry for many years.

As with core diameter, two methods of numerical aperture measurement became popular. Some laboratories determined

NA directly from the index profile, others from the far-field radiation patterns. Measurement round robins on a variety of fibers indicated that the NA could be determined from far-field patterns with a standard deviation of 2% [30]. However, those measurements differed from those obtained from the index profile by 4 to 8%, which was unacceptably large. Further studies and round-robin comparisons revealed that observed differences resulted from a combination of different wavelengths being used in typical implementations, and different definitions being applied to the profiles. For example, NA from far-field patterns used the 5% points on the profile to avoid noise in the baseline, whereas NA from the index profile is the theoretical maximum, with the cladding index as the baseline value. After corrections were applied, reasonable agreement could be obtained with the various techniques [31].

Fortunately, given the relatively large core sizes and NAs of common fibers, the practical solutions described above were adequate, and the more fundamental questions of which techniques were more "correct" were avoided. However, some measurements, most prominently measurements of multimode fiber bandwidth, were much more difficult and were not resolved until a decade or so later, when new applications for multimode fiber emerged.

IV. Optical Time-Domain Reflectometers (OTDRs)

It was recognized very early [7] that observing light backscattered from a pulse propagating in a fiber was a powerful diagnostic tool, and instruments developed on this principle have become ubiquitous in optical communications laboratories. However, the interpretation of OTDR signals can be difficult. Rayleigh scattering, refractive index variations, and other discontinuities contribute to the returned light. Other effects, including nonreflective losses (e.g., bends and some types of splices) variations in numerical aperture or other guidance properties, and, in multimode fiber, nonequilibrium mode distributions, can shape the backscattered waveform.

In specifying OTDRs, or in comparing their specifications, a variety of parameters are important: distance (time) resolution, dynamic range, and linearity in time and amplitude, among others [32]. However, since one of the greatest values of an OTDR is in locating defects or other artifacts within a fiber, the ability to accurately translate between observed time-domain measurements and distance along the fiber is particularly important. This requires very accurate knowledge of the group velocity in the fiber. One way to do this is through low coherence interferometry on relatively short lengths of identical fiber [33], which can give accurate values for the group velocity in specimens shorter than a meter in length.

Losses arising from nonreflective artifacts—for example, bends and high quality fusion splices located between identical fibers—can be evaluated from the discontinuities in the OTDR signal. However, if the fibers are not identical, odd effects, such as an apparent gain, can appear. These effects can be substantially minimized if the apparent splice loss is determined from both ends of the fiber and the results averaged [34], [35]. Connectors with air gaps and cracks or other types of defects may show significant reflections, corresponding in duration to the length of the pulse. In most cases, the losses of these artifacts can also be evaluated from the discontinuity in the scatter from sections before and after the artifact, particularly if results obtained from each end of the fiber are averaged. One caution about locating and identifying artifacts along the length of a fiber is that if two or more reflective artifacts are present, multiple reflections can lead to ghost signals.

OTDRs thus provide information about the properties of an optical fiber along its length that would be difficult to obtain in any other way but, though excellent precision may be possible, high accuracy is difficult to establish and measurements by OTDR are generally not regarded as appropriate for fiber specification.

V. Multimode Fiber Revisited—Gigabit Ethernet

Beginning in the mid-1980s, single-mode fiber replaced multimode fiber for nearly all network applications. But multimode fiber found a niche in low cost data links for local area networks where, with many connections, the low cost of multimode fiber connections was attractive. Moreover, multimode fibers could be easily coupled to inexpensive LED sources. Then, the development of the vertical cavity surface emitting laser (VCSEL) opened new technological opportunities. Milliwatts of power from VCSELs could be launched into multimode fiber cores and VCSELs could be directly modulated at rates from 1 to 10 Gb/s. At a wavelength around 850 nm, where VCSELs are readily fabricated and silicon detectors can be used, low cost links that operate at very high data rates can be developed.

It was soon apparent that the data rates and link lengths envisioned would push multimode fiber to its technical limits and, further, that the understanding and characterization of multimode fiber bandwidth developed in the 1970s and early 1980s were inadequate. Old, unsolved measurement problems began to be addressed by a new generation of metrologists. The measurement of differential mode delay (DMD), an old technique much improved by the 1990s, was the tool that led to a much better understanding of the dependence of bandwidth on index profile. An effort was initiated with the TIA and, in 1996, the FO-2.2 Task Group on Modal Dependence of Bandwidth was established.

Members of the Task Group performed round-robin comparisons and worked to improve DMD measurements. Initial comparisons indicated that multimode fiber bandwidth could be doubled on average compared to the standard overfilled launching used for specifying bandwidth. The VCSEL sources produce an underfilled launch so an enhanced bandwidth seemed possible. A frequency-domain phase shift technique based on methods developed to characterize single-mode fiber (see below) enabled high resolution DMD measurements on short lengths of fiber [36]. On these ($\sim$ 10 m) samples, mode-mixing was negligible. DMD measurements by the time-domain method were also improved through the use of picosecond mode-locked lasers [37]. In both of these improved DMD measurement schemes, a single-mode fiber was scanned across the core of the multimode fiber to excite limited mode groups.

A large round-robin comparison was conducted using nine 62.5-μm core fibers and six 50-μm core fibers selected to include a diverse range of bandwidth behavior. The fibers were

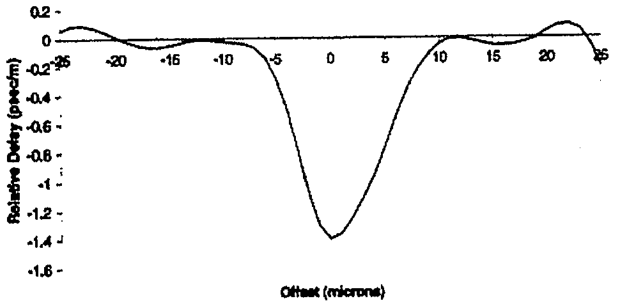

Fig. 4. Differential Mode Delay (DMD) of a 50-μm core fiber versus launch position on the core, showing a substantial difference near the center of the core.

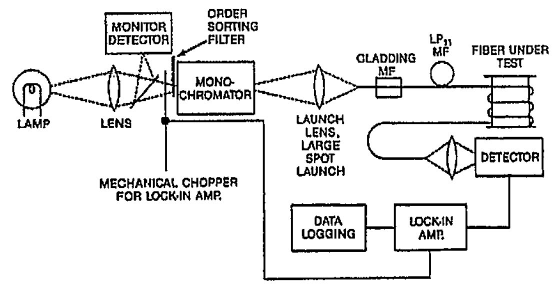

Fig. 5. Spectral attenuation test system.

placed in a single cable, and each participant received a 300-m length. A variety of launching conditions were used, and actual system transceivers were sent with the fiber. As with the experience from the 1970s, the overfilled launch produced the best interlaboratory agreement. It was also the most conservative measure of bandwidth. Considerable improvement in bandwidth was possible with a restricted launch [38]. However, subsequent studies identified fibers that exhibited a substantial decrease in bandwidth, with a very restricted on-axis launch. DMD measurements indicated these fibers showed a rapidly changing delay in the center region of the fiber with relatively flat delay for mid- and higher order modes [39] (Fig. 4). This is consistent with center-line errors in the index profile, which had also been observed in the early 1980s [40]. If these fibers are encountered in the installed base, a patch cord with an offset connector can be employed to restore the bandwidth. An even more extensive round robin followed, using 95 different fibers along with over 60 system sources [41]. One recommendation from the Task Group was that a 62.5-μm-core fiber was suitable for 1-Gbit/s Ethernet at lengths to 500 m if the bandwidth was at least 385 MHz/km as measured with a launch from a special 23.5-μm core fiber.

The industry also has a standard for using 50-μm core fiber for 10 Gb/s Ethernet and beyond. One proposal for a 100-Gb/s solution, useful to lengths of 100 m, is to use a ten-fiber ribbon of multimode fiber with a VCSEL array, with each laser modulated at 10 Gb/s [42].

VI. Single-Mode Fibers

Developing measurement techniques to meet the needs for single-mode fiber was fairly smooth since a large base of experience was available from the multimode fiber era. Attenuation measurements would still employ the "cut-back" method. "Bandwidth" measurements would consist of determining chromatic dispersion properties. And core diameter measurement was replaced by mode-field diameter measurement. "New" parameters included cutoff wavelength and polarization properties, and other geometrical parameters, such as cladding diameter, needed to be made with much greater accuracy.

Attenuation is perhaps the easiest parameter to measure in single-mode fiber and is the only parameter that NIST never tested in an interlaboratory round robin. Standards groups were satisfied with the precision and accuracy of their existing test methods. The most accurate procedure is the cut-back technique but, with single-mode fiber, the spectral attenuation is more important, so an incandescent lamp is typically used with a monochromator instead of interference filters. One important difference is that a mandrel wrap mode filter is generally needed near the source (within the 2-m cut-back length) to attenuate the second order LP_{11} mode (Fig. 5). This filter allows single-mode attenuation measurements to begin at approximately the cutoff wavelength of the fiber. With typical measurement apparatus, one standard deviation repeatability is in the range of 0.01–0.04 dB with a dynamic range of 25 to 35 dB [43]. Interlaboratory agreement of 0.03 dB/km has been reported [44].

Cutoff wavelength is measured with the same apparatus used for spectral attenuation measurements. This is not a particularly critical parameter, but practical systems are operated close to cutoff to enhance fundamental mode confinement. The cutoff wavelength measured is not the theoretical cutoff wavelength, but an "effective" cutoff wavelength, defined as that wavelength, λ_c, above which second-order mode power is below a given level compared to the fundamental mode power. It therefore depends on fiber length and curvature, so a standard test specimen consisting of a 2-m length of fiber containing one 28-cm-diameter loop is used; these conditions apply to both of the following methods.

One test method is sometimes referred to as the transmitted "power step." Here the relative spectral power transmitted through the 2-m length (with a large spot launch) is normalized to that transmitted through a short length of multimode fiber. As λ_c is approached from the long wavelength direction, an abrupt increase in power (step) is observed as the LP_{11} mode power begins to be transmitted. Cutoff is taken to be that wavelength at which the power has increased by 0.1 dB.

Another test method, called "single-bend attenuation," measures the spectral attenuation of a single wrap around a 4–6-cm diameter mandrel placed in the 2-m length. This is easily accomplished by taking the ratio of two spectral measurements, one with and another without the mandrel. A typical result is shown in Fig. 6. Here λ_c is defined as that wavelength at which the bend attenuation increases by 0.1 dB over the single-mode wavelength region. A preliminary interlaboratory comparison on three fibers, conducted by NIST among seven laboratories, using slightly different conditions for the standard test sample length and curvature than those described above, resulted in one standard deviation measurement spreads of 6 to 12 nm for the

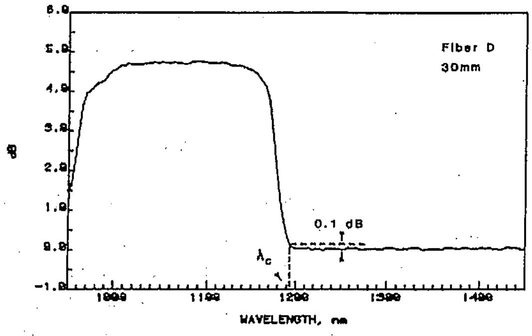

Fig. 6. Cutoff wavelength determined by the single-bend attenuation method.

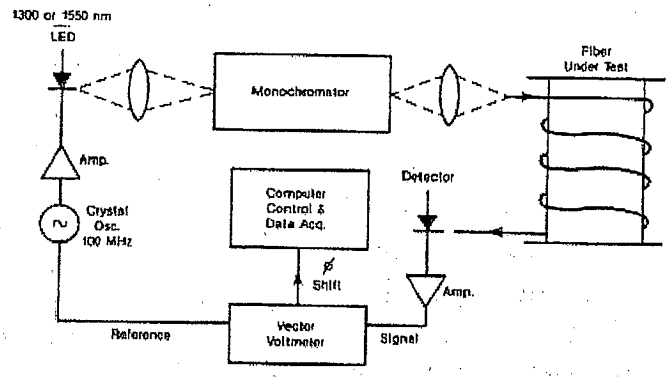

Fig. 7. Frequency-domain dispersion measurement test system using an LED and a monochromator.

power step and single-bend attenuation methods [45]. No systematic differences were observed between the two methods.

Chromatic dispersion—the variation of group velocity with wavelength—leads to pulse broadening when sources with finite spectral width are used. In single-mode fiber, both material properties and waveguide parameters contribute to chromatic dispersion. It may be specified as the variation in group delay with wavelength, $\tau(\lambda)$, or by the chromatic dispersion coefficient, $D(\lambda)$, which is defined as $d\tau/d\lambda$. Of special interest is a determination of the wavelength, λ_0, where D is zero. In ordinary single-mode fiber, material dispersion dominates and λ_0 is near 1300 nm, but by designing the refractive index profile carefully, it is possible to shift λ_0 to a wavelength near the attenuation minimum at 1550 nm or to otherwise control the variation of dispersion with wavelength. These fibers are typically known as dispersion-shifted or dispersion-flattened fibers.

Measurements of chromatic dispersion on single-mode fiber are refinements of methods used with multimode fiber. Early measurements were made with tunable pulsed sources. One popular source was the fiber Raman laser [46] which, when filtered with a monochromator, could produce tunable 100-ps duration pulses. Relative time delay of the pulses as a function of wavelength was used to determine D. Sets of individual pulsed laser diodes (typically 5) were also used and the results fitted to theoretical expressions to obtain D [47]. A comparison of the Raman fiber method to the discrete laser diode method on ten fibers gave λ_0 with an average absolute difference of 1.2 nm [48].

However, the industry generally adopted CW frequency-domain techniques. A CW source is modulated at an RF frequency, and a vector voltmeter is used to determine relative phase delay (effectively time delay) as the wavelength is tuned. An elegant implementation of this technique is shown in Fig. 7 [49]. A broadband LED is modulated at an RF frequency with a crystal quartz oscillator, a monochromator selects a portion of the spectral emission, and a vector voltmeter determines the relative phase shift as the monochromator is tuned. The resulting $\tau(\lambda)$ is differentiated to obtain D. An adaptation of this technique is the differential phase shift method [50]. In this technique, the wavelength is also modulated (as if the monochromator grating were dithered) at a low frequency, and a lock-in amplifier determines D directly (no differentiation is necessary).

A round-robin comparison of chromatic dispersion measurements was conducted among TIA members using seven fibers [51]. Participants used the phase shift, differential phase shift, and time-domain techniques. For unshifted fibers, the group delay data was fit to a three term Sellmeier equation, and the average one standard deviation agreement for λ_0 was 0.93 nm. The one standard deviation agreement for the dispersion coefficient at one wavelength (1310 nm) was 0.08 ps/(nm/km). While there was no discernable systematic disagreement between measurement methods, there were noticeable systematic offsets between laboratories. For the longer fibers in the study, the average standard deviation of these offsets for zero dispersion wavelength was 0.16 nm. This is an indication of the random error of a particular laboratory's measurements and suggested the need for calibration fibers. For several years NIST produced and provided such fibers as a Standard Reference Material (SRM 2524) and subsequently has provided Special Tests of chromatic dispersion measurements on customers' fibers. [52]

As systems operating with modulation rates of 10 to 40 Gb/s were being developed, it became apparent that polarization effects, which came to be called polarization mode dispersion (PMD), could be a further limitation. PMD can result in pulse broadening and, if components with a polarization-dependent loss (PDL) are present, in signal fading. In an ideal single-mode fiber, with perfect circular symmetry, no internal stress, and no externally applied stress (for example from bending or squeezing) the velocity of light would be the same for all polarization states. But real fibers exhibit all of these effects, leading to birefringence that varies along the length of the fiber, and with temperature and other environmental factors. It is therefore not surprising that it is possible to characterize the PMD of a fiber only as a statistical quantity [53, ch. 12], [54].

For any sufficiently narrow wavelength range, there exist two orthogonal polarization states that represent the fastest and slowest group velocities in the fiber. These are known as the principal states of polarization (PSPs) and, for them, one can define and measure a differential group delay (DGD) [55]. As a practical matter, most fiber is specified with a mean value of DGD (usually in picoseconds), and perhaps a value for a PMD coefficient, (usually in ps $\cdot$ km$^{-(1/2)}$), which reflects the length dependence of a fiber in which the birefringent elements are highly randomized (the fiber is "randomly mode-coupled").

A full specification of PMD would involve knowing the principal states and the associated DGD over the wavelength

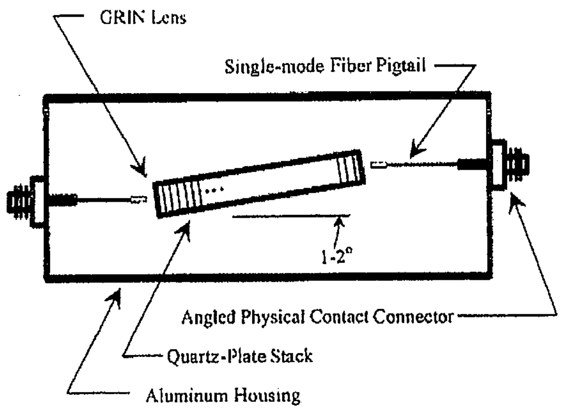

Fig. 8. Diagram of mode-coupled PMD calibration artifact: NIST SRM 2518.

range of interest.[4] Wavelength dependence becomes important at higher data rates, particularly in the presence of chirped sources, and when PMD compensation is employed.

Second-order PMD includes two components of this wavelength dependence. One behaves as a polarization-dependent component of chromatic dispersion (PCD) that is stochastic and can yield pulse broadening or compression. The other arises from shifts in the principal states with wavelength and is commonly known as PSP depolarization; it can cause substantial pulse distortion and seriously complicate efforts at compensation.

Many techniques can be used to characterize PMD ([53, ch. 12] and [54] provide two good summaries), but since the DGD of fiber varies with environmental conditions and wavelength, determining the quality of those measurements is challenging. One solution is to create calibration artifacts that mimic the properties of fiber, but are stable and thus accurately measurable.

A calibration standard developed at NIST [58] (Fig. 8) consisted of a stack of 35 quartz plates, with their optic axes perpendicular to the direction of propagation and pseudorandomly oriented to each other. Thirty of the plates had a thickness of 2.0 mm, and the remaining five, 1.2 mm thick, were randomly located in the stack. Testing showed that the PMD characteristics of the plate were qualitatively similar to those of a 25-km-long fiber. In 1999, these standards became available as NIST Standard Reference Material 2518, and were certified to have DGD values in the neighborhood of 0.4 ps, with uncertainties ($K = 2$) around 2%.

Since the presence of both PDL and PMD can lead to signal fading, it may be important to characterize the wavelength-dependent PDL of a system or subsystem. PDL is generally defined as the ratio of the maximum to minimum transmittance over all polarization states. Measurement methods generally involve measuring the transmittance for polarizations corresponding to some fraction of the Poincaré sphere [59], [60]. The number and choice of measurement states then determines the accuracy, speed of measurement, and amount of analysis required.

Another important parameter for single-mode fiber is the mode-field diameter (MFD), differences in which result in

[4]For in-depth discussions of polarization mode dispersion, see [56] and [57].

MODE-FIELD DIAMETER—FAR-FIELD (FF)

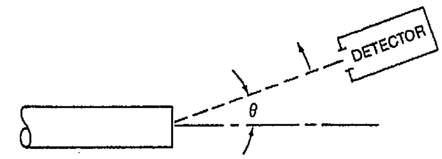

Fig. 9. Simple far-field measurement to determine mode-field diameter.

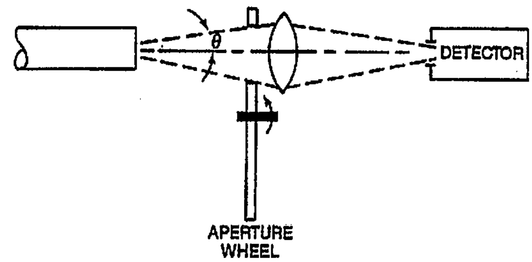

Fig. 10. Schematic of the VAFF method of mode-field diameter measurements.

intrinsic joint loss—a mismatch of 10% in MFD gives rise to 0.05-dB loss. The methods for measuring MFD can be divided into near-field and far-field techniques.

One can directly measure MFD in the near-field (NF) by a 1-D scan of the magnified image of the fiber end-face [61]. The system magnification must be known accurately. Another near-field technique is the "transverse offset" (TO) method, in which the test fiber is cleaved, and a butt splice is made between the two end-faces [62]. With index matching liquid between the fibers, the power transmitted through the splice is recorded as one fiber is transversely offset. This requires accurate absolute measurements of very small displacements. In both of these near-field methods, a Gaussian in intensity profile is normally assumed, and the mode-field diameter is defined as the diameter where the intensity has decreased to $1/e^2$.[5] Both of these techniques have largely been supplanted by easier, but indirect, far-field techniques.

Perhaps the easiest of the far-field techniques is the 1-D far-field (FF) scan. An apertured detector is rotated in the far-field of the fiber end-face through maximum intensity to obtain the far-field intensity distribution, Fig. 9. This is usually accomplished with a simple rotary stage; no optics are necessary. Again, a Gaussian shape for the far-field profile is fit to the distribution, and the angle, θ, where the far-field distribution has decreased by $1/e^2$ is determined. The MFD is given by $2\lambda/\pi \tan\theta$. Since only a small portion of the emission from the fiber is detected, a laser diode source is usually necessary.

Another far-field method in common use is called the "Variable Aperture Far-Field" (VAFF) method [63]. In this method the far-field power is collected by a lens and focused onto a detector (Fig. 10). An aperture wheel with up to 17 apertures is rotated in front of the lens to give the power collected in various far-field cone angles. Since a large fraction of the power from the fiber is collected, there is usually sufficient signal-to-noise ratio to use an incandescent lamp with an interference filter. Again,

[5]The Gaussian definition was initially used and is fairly accurate for dispersion unshifted fiber. However, it was eventually replaced by the "Petermann" definition, which is more applicable to all classes of single-mode fiber.

a Gaussian far-field is assumed, and the power collected for a number of cone angles is fit to that assumption. This particular method has become popular and commercial instrumentation exists.

NIST conducted an early round robin on MFD among TIA members [64]. Five single-mode fibers were measured at both 1300 and 1550 nm. Gaussian fits were assumed for the TO, NF, FF, and VAFF methods. At 1300 nm, the overall average one standard deviation agreement was 0.15 μm for MFDs in the 8–11-μm range. No distinct systematic offsets between methods were observed. However, at 1550 nm, distinct offsets were observed between methods. At 1550 nm (further from the cutoff wavelength) the mode shapes are not as Gaussian, and this was responsible for the systematic offsets. Mathematical modeling that assumed a step index profile fiber where mode profiles can be expressed in closed form predicted the observed offset between FF and VAFF methods.

In some fibers, including many in which the index profile has been designed to shift the dispersion, the assumption of a Gaussian mode profile is not adequate. For these fibers, an alternative definition known as the "Petermann" spot size and based on the second moments of the far field proved useful [65]. When the mode profile is Gaussian, the Petermann MFD reduces to the Gaussian definition. A second round robin and other studies confirmed the usefulness of the Petermann MFD [66], [67]. The comparisons involved six single-mode fibers, four dispersion unshifted and two dispersion shifted. Offsets between the FF and VAFF were reduced on all classes of fiber at both 1300 and 1550 nm; however there was still a noticeable offset on the dispersion-shifted fiber at 1550 nm. Further study indicated that the small MFD (wide far-field) common to this class of fiber required VAFF apparatus with larger collection angle. With increased collection, the offsets were eliminated. A VAFF system using mirror optics for wide angle collection was shown to eliminate the offset [68]. The Petermann definition is now written into industry test procedures for all classes of single-mode fiber.

Another area of dimensional measurements is generally referred to as fiber "geometry," and includes the measurement of cladding diameter, cladding circularity, and mode-field/cladding concentricity, all of which affect splice and connector loss. For example, in order to use low-cost connectors that do not require adjustment, the tolerance on cladding diameter needs to be ± 1 μm; a measurement accuracy of about ± 0.1 μm is required to support this tolerance.

Numerous methods were developed, but for routine measurements a method known as the grayscale video microscope (Fig. 11) soon dominated because it was easy to perform and provided excellent precision. It basically consists of an automated video microscope in which the fiber end-face is imaged by a microscope objective onto a detector array. The fiber is illuminated in diffuse white light, and white light is transmitted through the core to display the core region. A mathematical algorithm is used to curve fit points along the cladding edge. Preliminary measurements showed that on a single test set the technique could be very precise, with round-robin testing giving a standard deviation of 0.03 μm, but much greater systematic offsets were found between laboratories [51].

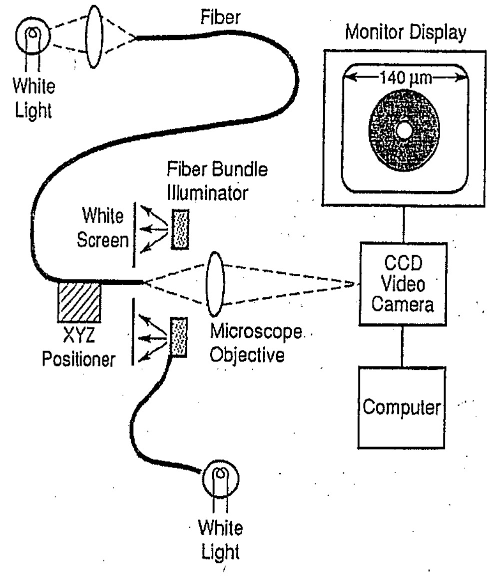

Fig. 11. Grayscale method of determining fiber geometry measurements.

A calibration standard was obviously needed, and both NIST [69] and the National Physical Laboratory in the U.K. [70] set out to provide such an artifact. It soon became apparent that an actual fiber end face with an accurately known diameter was needed, because differences in illumination and diffraction cause uncertainties in the edge determination [69].

Interferometric methods were one choice for measuring the standards. A typical approach is to use a white light interference microscope and observe the fiber sample in a transverse direction [71], typically against an optical flat. Michelson or Mirau objectives are used and a laser interferometer monitors the position of the microscope stage. The top surface of the fiber is located by its central white light fringe. Then the stage is moved to obtain the central white light fringe of the surface of the optical flat; the cladding diameter is the difference between the two positions. A noncontact version of this method has also been developed [72]. In this case, the bottom surface of the fiber is observed through the fiber; however, a significant correction due to the refractive index of the fiber is necessary. A contact system developed at NIST that uses a Mirau objective could determine cladding diameter with an uncertainty of ± 30 nm [73].

Alternatively, contact micrometers that operate, in principle, like a typical machine shop micrometer can be used [74], [75], except that the force of contact is sufficient to distort the fiber by an amount comparable to the desired uncertainty. A contact micrometer built at NIST is based on a design initially used to measure wire thread gages. It contacts the fiber between two hardened steel surfaces, one flat and moveable and the other cylindrical and stationary, with the separation determined by a laser interferometer. To compensate for deformation of the fiber, the apparent fiber diameter is measured against contact force and the results extrapolated to zero force. The uncertainty of a cladding diameter with this instrument is ± 50 nm.

The NIST contact micrometer and white light interference microscope were compared, along with a third option, a confocal microscope [76]. A comparison on several fibers indi-

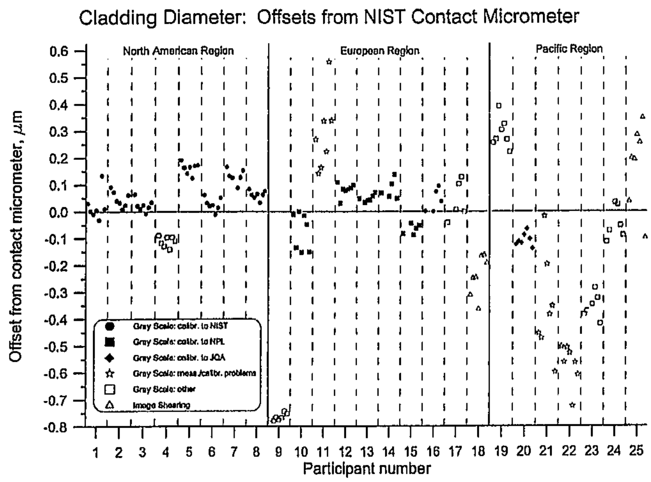

Fig. 12. Results from the final international comparison of fiber diameter measurements showing the improved agreement for measurements referenced to calibration standard (solid points).

Wavelength nanometers	Frequency THz	Wavelength nanometers	Frequency THz
1530.334	195.9	1547.715	193.7
1531.116	195.8	1548.515	193.6
1531.898	195.7	1549.315	193.5
1532.681	195.6	1550.116	193.4
1533.465	195.5	1550.918	193.3
1534.250	195.4	1551.721	193.2
1535.036	195.3	1552.524	193.1
1535.822	195.2	1553.329	193.0
1536.609	195.1	1554.134	192.9
1537.397	195.0	1554.940	192.8
1538.186	194.9	1555.747	192.7
1538.976	194.8	1556.555	192.6
1539.766	194.7	1557.363	192.5
1540.557	194.6	1558.173	192.4
1541.349	194.5	1558.983	192.3
1542.142	194.4	1559.794	192.2
1542.936	194.3	1560.606	192.1
1543.730	194.2	1561.419	192.0
1544.526	194.1	1562.233	191.9
1545.322	194.0	1563.047	191.8
1546.119	193.9	1563.863	191.7
1546.917	193.8		

Fig. 13. ITU WDM grid. The frequencies are exact and the wavelengths are computed from the frequencies.

cated the contact micrometer and interference microscope typically agreed within a few nanometers. The confocal microscope showed an average systematic difference of 20 nm between the other two methods [77].

Based on the comparisons and relative measurement ease of the contact micrometer, it was chosen as the NIST calibration method for fibers supplied to the industry as Standard Reference Materials (SRMs). SRM 2520 became available in 1992 as a pristine, cleaved fiber end enclosed in a protective metal housing that could be easily inserted in most grayscale measurement systems. The diameter of these SRMs is typically certified to better than ±50 nm.

A final interlaboratory comparison on single-mode fiber diameter, involving laboratories around the world, was completed in 1994 [78]. The results made a very strong case for the use of good standards for the calibration of grayscale diameter measurement systems. Among North American laboratories, the average one standard deviation measurement spread for cladding diameter on seven fibers was reduced to 0.08 μm (Fig. 12) a significant improvement from an earlier comparison among North American laboratories held in 1992 which exhibited a spread of 0.114 μm. Industry standard test procedures (FOTPs) for the grayscale method now require the use of a calibration fiber.

VII. Wavelength Measurements

For the first two decades or so of optical communications development, highly accurate, or even highly precise, wavelength measurements were not a significant problem. Most systems operated at a single wavelength, or at most two or three well separated wavelengths. But when the optical fiber amplifier enabled dense wavelength division multiplexing (WDM), and when a standard grid of optical frequencies was established by the ITU, accurate optical frequency or wavelength measurements quickly became an important issue. The original ITU grid (Fig. 13) was specified with a spacing of 100 GHz between channels. Demonstration experiments soon showed that it would be possible to subdivide the ITU grid by a factor or two or four, leading to a fractional channel spacing ($\Delta v/v$ or $\Delta\lambda/\lambda$) on the order of 10^{-4}.

Optical frequency or wavelength measurements with a fractional accuracy approaching 10^{-6} were thus needed. This was not an unprecedented accuracy. During the 1970s, the development of frequency stabilized lasers and techniques to relate their frequency [79], [80] and wavelength [81] to international standards led to a redefinition of the meter in terms of the speed of light in vacuum [82].[6] Those developments also provided a large number of stable and accurately measured laser frequencies in the near infrared and visible regions that could be used in interferometers to determine the frequency or wavelength of unknown sources. Early experiments [84] demonstrated the ability to measure laser frequencies to a fractional accuracy of around 2×10^{-7}.

As WDM techniques began to be more widely developed in the 1990s, most wavelength measurements in optical communications were performed with optical spectrum analyzers. These were generally sophisticated instruments based on grating spectrometers, but at the time most provided measurements with uncertainties in the range of 0.1 or 0.2 nm in the near infrared, which is equivalent to a fractional uncertainty comparable to the channel spacing in the more dense WDM systems. Furthermore, accurate absolute calibration was difficult.

The first major thrust toward improved wavelength measurements was to develop calibrations standards that could be used with optical spectrum analyzers or other instruments to improve their accuracy and monitor their stability. Certain gas molecules happen to have rich absorption spectra in the areas of interest for optical communications, among them acetylene $^{12}C_2H_2$, in the 1510–1540-nm region, hydrogen cyanide, $H^{13}C^{14}N$, in the 1530–1560-nm region, and carbon monoxide, $^{12}C^{16}O$, and $^{13}C^{16}O$, in the 1560–1630-nm region. After considerable research into pressure shifts and broadening in these gasses, NIST was able to produce relatively simple absorption cells (Fig. 14)

[6]Documents concerning the new definition of the meter can be found in [83].

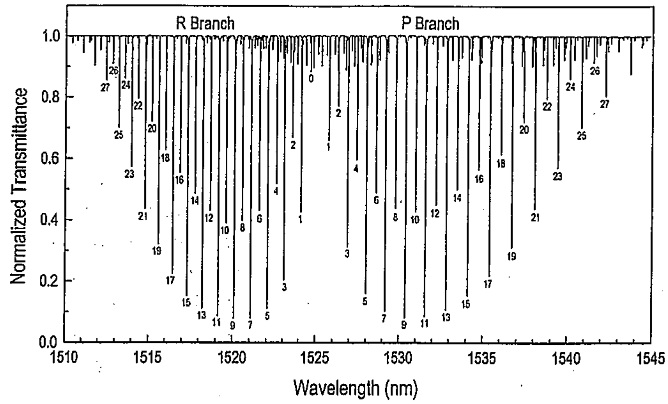

Fig. 14. Spectrum from an acetylene absorption cell.

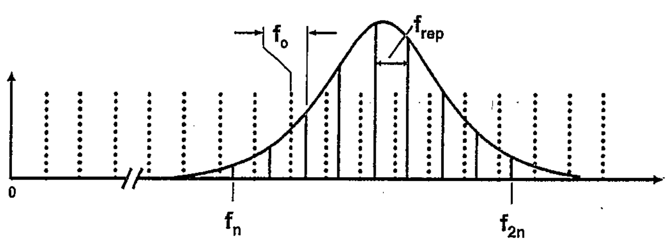

Fig. 15. Comb of optical frequencies (solid lines). If the repetition rate is accurately known, the frequency offset f_o can be determined by comparing the second harmonic of f_n with f_{2n}, and the absolute frequencies of the comb lines are thus determined.

with nearly 200 lines in which the line centers could be certified with expanded uncertainties ranging from 0.04 pm to 0.7 pm [85]–[87]. These cells are available from NIST as Standard Reference Materials, and can be used with broadband sources, such as LEDs, or tunable lasers, in instrument calibration.

For the ultimate in optical frequency measurements, optical comb technologies now being developed in several laboratories are particularly exciting [88]. Starting with a stable, mode-locked laser that may, for example, produce a comb of precisely spaced optical frequencies spanning as much as 100 nm, a much broader comb with the same frequency spacing can be produced by passing the laser output through a highly nonlinear medium, such as a microstructure or photonic-crystal fiber. And if such an expanded comb can be made to extend over a full octave in frequency, it is possible to establish the absolute frequencies of the individual lines in the comb, as shown in Fig. 15. The comb of optical frequencies, depicted by the solid lines under the optical envelope, is spaced at frequency intervals equal to the pulse repetition rate of the laser, f_{rep}. This comb is offset by a frequency f_o from an imaginary comb having the same frequency intervals, f_{rep}, but starting at zero frequency, the imaginary comb being depicted by the dotted lines. If, then, a line near the low-frequency end of the spectrum, $f_n = nf_{\text{rep}} + f_o$ is doubled in a nonlinear medium, and the difference between that frequency, $2f_n = 2(nf_{\text{rep}} + f_o)$, and the line near the high end of the spectrum with frequency $f_{2n} = 2nf_{\text{rep}} + f_o$ is determined using a heterodyne detector, the output frequency is f_o. Thus the absolute frequencies in the expanded laser comb can be known exactly.

VIII. Summary

The measurements described above are only a fraction of those that were needed by the emerging optical fiber industry, but they illustrate a process for the establishment of measurement standards that is unusual, if not unique, in new technologies. It was exceptionally collaborative; all parties with a legitimate interest were welcome to participate. Where competitive interests made collaboration difficult, a neutral and independent party (NBS/NIST) was often able to assist. There was a spirit of finding technically sound and consistent solutions while accommodating the needs of individual manufacturers and their customers. All parties preferred simple measurements; in some cases that was possible but in others complexity became essential. Some measurements that initially appeared simple, or gave precise results in a single laboratory, were difficult to replicate in other locations. It became important to differentiate situations where a better procedure was needed from those where a calibration artifact could provide the necessary accuracy. Interlaboratory comparisons provided the essential data for making those judgments. And thus, perhaps the most important lesson learned was the importance of validating new methods through industry-wide testing.

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