Proc., Measurement Science Conf. 2000
Anaheim, CA, Jan 19-21, 2000
Session IIB

NIST ARTIFACT STANDARDS FOR FIBER OPTIC METROLOGY

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Abstract - The primary means of transferring fiber optic calibration metrology at the National Institute of Standards and Technology is through artifact standards called Standard Reference Materials (SRM). NIST currently provides SRMs for fiber geometry (fiber cladding diameter and coating diameter, ferrule inner and outer diameter), and fiber propagation characteristics (mode-field diameter and chromatic dispersion). Also soon to be available are SRMs for polarization-mode dispersion and polarization-dependent loss in fibers. This paper will discuss the characteristics, applications and impact of these artifact standards.

INTRODUCTION

Optical fibers have been around for a long time, but they are still an important technology which is enabling huge leaps in the telecommunications industry. And, although fiber optic metrology has existed as long as the fibers themselves, there are still new aspects of fiber measurement to be solved.

The purpose of this paper is to give a general overview of some of the metrology issues in the fiber optics industry. An appropriate vehicle for this purpose is a description of the variety of fiber optic artifact standards that are available at the National Institute of Standards and Technology (NIST).

The parameters affecting a fiber's performance can be divided into two categories: geometrical properties and propagation characteristics. This oversimplification allows a fiber to be described based on either its physical dimensions or the way in which light propagates within the fiber. One way in which NIST transfers its calibration metrology to industry is by providing artifact standards known as Standard Reference Materials (SRM). Following is a discussion of the NIST fiber optic SRMs.

FIBER GEOMETRY

Single-mode fiber performance depends on accurate characterization of the fiber's geometry. The cross-section of Figure 1 illustrates a generic single-mode fiber profile. Light travels in the ~ 9 μm silica glass core of the fiber. The core is typically doped with germanium or other "impurities" in order to raise the index of refraction above that of the silica cladding, thus enabling total internal reflection. The cladding is surrounded by a polymeric coating that protects the glass from damage.

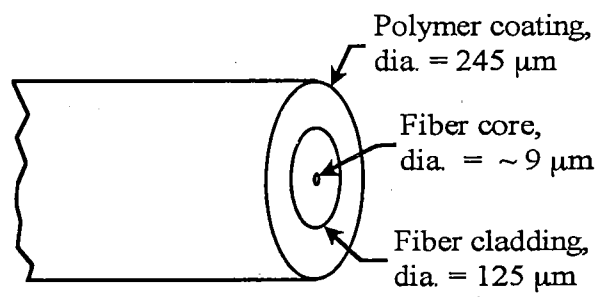

Figure 1. Cross section of single-mode optical fiber.

Fiber Cladding Diameter

In 1970, the development of a low-loss (high-purity) glass composition reducing the fiber optic transmission loss coefficient to 20 dB/km signaled the entrance of optical fibers into the telecommunications arena [1]. Today, fiber loss coefficients have been drastically reduced to the order of 0.2 dB/km, but on this level, a new loss mechanism becomes significant: fiber-to-fiber connection loss. A 1 μm misalignment of the fiber cores can cause a 0.2 dB (5%) loss across the splice [2]. This loss adds up along a communication link, which has multiple splices.

In order to facilitate low-cost and low-loss connections, the fiber's cladding diameter must be uniform and well characterized. In simple fiber

connections, the fiber polymer coating is stripped away and the fiber is aligned according to the cladding. As a result, the fiber optic industry requires measurements of cladding diameter to an accuracy of 0.1 μm. In support of this, NIST developed a fiber artifact standard (SRM 2520) whose cladding diameter is certified to within 0.04 μm. This artifact is an approximately 2 m piece of single-mode fiber whose cladding diameter has been certified using a contact micrometer [3]. The cladding diameter of the specimen fiber was measured at four different angular orientations. An approximately 0.28 μm correction is added to compensate for the 0.2 N compressive force applied to the fiber during the measurement.

The release of SRM 2520 in 1993 allowed the major U.S. fiber manufacturers to re-calibrate their draw towers to reduce fiber cladding diameter uncertainty by a factor of 2.

Fiber Coating Diameter

Accurate measurement of the fiber's coating diameter is also important. Often, fibers are identified by a colored polymeric coating (nominally 2.5 μm thick) that is applied over the ~ 245 μm diameter polymeric coating. Accurate measurement of the fiber's polymeric coating allows more accurate processing as the final colored layer is added. Accuracy of fiber coating diameter is also important in high-volume ribbon fibers where multiple single-mode fibers are joined side-by-side. The fibers are separated by their diameters, and uniform diameter means uniform spacing, which again affects coupling loss.

NIST supports fiber coating diameter with three artifact standards (SRMs 2553, 2554 and 2555). The artifacts are not coated fibers, but rather glass rods of nominally 250 μm diameter and with indices of refraction similar to those of typical polymeric coatings (the three different SRM numbers correspond to three different indices, 1.504, 1.515 and 1.535, respectively). The rods are made of glass in order to avoid any degradation that might occur to a polymeric coating over time and with exposure to index-matching oils etc. The diameters of these rods were measured using a contact micrometer in a procedure similar to that used for the cladding diameter artifacts.

Connector Ferrule (Inner Diameter)

Fibers can be connected together by two means: splicing or connectorization. In the case of connectorization, bare fibers are stripped of their polymeric coatings and are cemented into a ferrule, shown in Figure 2. Two connectorized fibers can be connected together by sliding them into a sleeve, where low-loss alignment now requires not only repeatable fiber geometry, but also well-characterized ferrule geometry. NIST has developed two artifacts to aid in the calibration of connector geometry: ceramic ferrules calibrated for their outer diameter and steel pin gauges calibrated for the inner diameter of the ferrule.

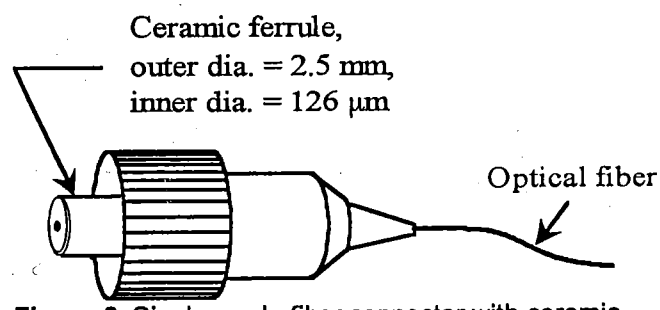

Figure 2. Single-mode fiber connector with ceramic ferrule.

Clearly, the ferrule's inner diameter tolerance is critical to make the fiber fit snugly so that its core is well centered. The artifact for inner-diameter calibration (SRM 2522) is a 60 mm long steel wire of nominal 125 μm diameter, certified over a 10 mm central portion of the wire to 0.042 μm, by use of the contact micrometer. In practice, a ferrule's inner diameter is measured with a set of pin gauges of various diameters. The inner diameter is bracketed by the diameter of the largest pin gauge that fits and that of the smallest pin gauge that doesn't.

The NIST artifact itself is not intended to be inserted into a ferrule. Rather, its use is in calibrating the contact or laser micrometer used by the researcher to measure the diameters of their own pin gauge set.

Connector Ferrule (Outer Diameter)

Calibration of ferrule outer diameter is provided by SRM 2523, which is a ceramic ferrule of nominal 2.5 mm outer diameter certified to an uncertainty of 0.05 μm (using the contact micrometer).

Mode-Field Diameter

One obvious geometrical parameter has not yet been mentioned - fiber core diameter. However, the more practical measurement is of the area occupied by the propagating light within the fiber. A fiber's mode-field diameter (MFD) is essentially the spot size of light (the $1/e^2$ intensity point for a Gaussian profile) and depends on the fiber's refractive-index profile. MFD is useful in considerations of splicing losses and fiber bending.

MFD can be measured either in the near-field by direct measurement or in the far-field by scanning the transverse intensity profile and relating it to MFD via a Hankel transform. SRM 2513 is a 2 m fiber characterized for MFD with a 0.03 μm uncertainty. The measurements were carried out using a direct far-field measurement system [4].

PROPAGATION CHARACTERISTICS

The second class of fiber characteristics relate to the manner in which light is perturbed during its propagation in the fiber. Examples for which NIST offers (or plans to offer) Standard Reference Materials are: chromatic dispersion, polarization-mode dispersion, and polarization-dependent loss. These characteristics are related to the fiber's index of refraction and its distribution, but practically, it is not possible to determine them based on direct measurements of index. Instead, these characteristics are measured by launching light into the fiber and measuring the way the light is perturbed by that propagation.

Chromatic Dispersion

In the time domain of high-speed digital communication, the fundamental limit to the data rate is in how closely two optical pulses may be spaced and still be distinct when they exit the fiber communication link. A major limiting factor is pulse-spreading due to chromatic dispersion, which refers to the wavelength dependence of a fiber's group index of refraction. Since the laser source has a finite linewidth, chromatic dispersion causes the different wavelengths contained in laser pulses to travel at different speeds, thus spreading the pulses in time.

Chromatic dispersion in fibers comes from a combination of material dispersion of the doped glass and waveguide dispersion due to the fiber's geometry. These two sources contribute dispersions that can be of opposite sign, and so, there can exist a wavelength at which the total dispersion is zero. This zero-dispersion wavelength λ_0 occurs near 1550 nm in dispersion-shifted fiber (DSF), which is commonly used in telecommunications systems. Of course, for a single-channel system, the best performance is obtained when the laser's output is centered on λ_0. Therefore, accurate measurements of λ_0 are important.

NIST assists in the calibration of chromatic-dispersion measurement systems by offering an artifact standard for chromatic dispersion (SRM 2524). This artifact consists of a spool of 10 km of dispersion-shifted optical fiber whose zero-dispersion wavelength is measured to an uncertainty of approximately 0.06 nm, and the dispersion slope (change in dispersion with respect to wavelength) at λ_0 is measured to an uncertainty of approximately 0.008 ps/nm^2. These values are certified using a frequency-domain phase-shift measurement system [5] where light from an RF-modulated laser is sent down the fiber and detected such that the phase of the RF modulation with respect to the electrical modulating signal is measured. Since RF phase is related to the group delay in the fiber, recording RF phase as the laser wavelength is tuned yields a measurement of group velocity dispersion (GVD). GVD is proportional to the wavelength derivative of the RF phase. The zero-dispersion wavelength is strongly temperature dependent, with a coefficient of +0.030 nm/°C. The SRM is certified for measurements at 23 °C, but the certified values can be extended to nearby temperatures using the thermal coefficient.

Polarization-Mode Dispersion

Polarization-mode dispersion (PMD) is another dispersive effect that results in pulse spreading. Birefringence in the transmission fiber creates a polarization-dependent propagation (group) velocity within the fiber. Defects or microbends in the fiber reorient the light's polarization state, causing the fiber following the defect to act as a separate section with birefringence equal to that of the first section, but with a new eigenaxis. The fiber can be modeled as a collection of birefringent sections with randomly-oriented axes. Long lengths of fiber have many such sections and are referred to as highly polarization-mode-coupled.

Highly polarization-mode-coupled fiber acts to broaden the optical pulse, as shown in the time-domain picture of Figure 3. A pulse traveling in the

fiber will have its polarization state projected onto the fast and slow axes of each birefringent element it encounters. The pulse will be split into a fast- and slow-traveling component with the relative power in each being determined by the orientation of the birefringent axis with respect to the incoming polarization state. The multiple birefringent elements in the fiber split each pulse multiple times, and an input pulse emerges as a collection of 2^N pulses (N is the number of birefringent sections) with a Gaussian temporal distribution. Since the maximum temporal splitting of the pulses is much shorter than the coherence time of the source, the collection of pulses adds coherently and the result is a broadened pulse. PMD is a measure of this pulse broadening.

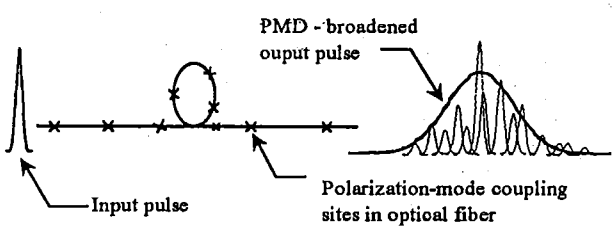

Figure 3. Time-domain illustration of pulse spreading due to polarization-mode dispersion in highly polarization-mode-coupled fiber.

The difficult part about PMD measurements on long fibers is that the orientations and strengths of the multiple birefringence elements depend on environmental conditions. So the PMD becomes a statistical quantity with standard deviations typically on the order of 15 to 25% [6]. These large measurement variations make calibration difficult.

In order to aid this situation, NIST has developed an artifact standard for mode-coupled PMD (SRM 2518) [7] which simulates the PMD effect of fiber, but without the statistical uncertainty. The artifact design shown in Figure 4 attempts to emulate the multiple-birefringent-section model of fiber by stacking roughly 35 quartz waveplates with randomly oriented birefringent axes and then pigtailing the device.

The device is certified by the frequency-domain measurement technique of Jones matrix eigenanalysis (JME) [8]. This technique measures the Jones polarization transfer matrix of the test device at closely-spaced wavelength pairs over a broad wavelength range. For SRM 2518, this wavelength range is limited by the tunability of the laser to about 90 nm. From the two Jones transfer matrices at each wavelength pair, the PMD is derived as the wavelength average of the

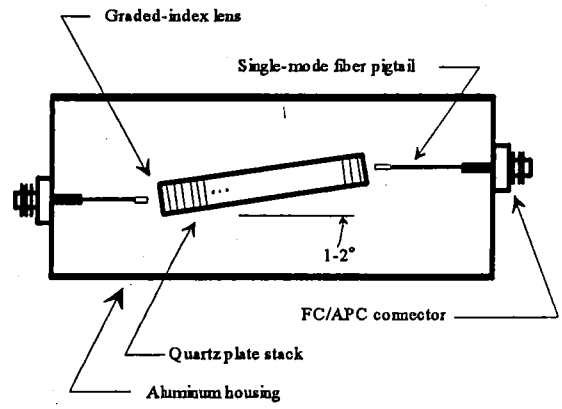

Figure 4. Diagram of the polarization-mode dispersion artifact (SRM 2518).

polarization eigenvalues of the test device. The nominal PMD of the device is 0.5 ps, with an uncertainty of approximately 0.005 ps.

This artifact serves to calibrate JME measurement systems for fiber measurements. However, other PMD measurement techniques exist that are not covered by this artifact (low-coherence interferometry and the fixed-analyzer technique). We plan to develop a second artifact that is a single birefringent waveplate with fiber pigtails which will be calibrated for all available measurement techniques.

Polarization-Dependent Loss

Polarization dependent loss (PDL) is another polarization effect which degrades lightwave telecommunication system performance. While it occurs in both components and fibers, the primary source of PDL in most networks is the component contribution. As the name implies, PDL is a loss mechanism which is dependent on the polarization state of the light, and is defined as

$$PDL = 10\log(T_{\max} / T_{\min}),$$

where Tmax and Tmin are the maximum and minimum transmittances found for all possible input polarization states.

PDL can degrade the bit error rate of a system by converting fluctuations in the state of polarization into fluctuations in the transmitted intensity. The light's polarization state will change as temperature or other environmental conditions cause the system's intrinsic birefringence to drift.

Typical telecommunications systems have total PDL values of several dB. However, the individual components in a system are the major contributors to the PDL. Component PDLs can be between 0.05 and 0.5 dB. Therefore, for component PDL specification, resolutions of the order of < 0.01 dB will be required.

The NIST PDL measurement system uses a deterministic fixed-states method to derive Mueller matrix elements corresponding to PDL [9]. The measurement system is capable of 0.001 dB resolution. We are in the process of developing an artifact standard for PDL based on a short (~ 2 to 10 mm) section of polarizing fiber spliced to a single-mode fiber on the input end and a 40 m section of multimode fiber on the output end. The multimode fiber acts as a depolarizer to counteract the effect of PDL in the detector. This artifact will have nominally 0.1 dB of PDL.

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