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FIBER OPTIC MEASUREMENT CONSIDERATIONS FOR THE AEROSPACE INDUSTRY: LESSONS LEARNED FROM TELECOMMUNICATIONS

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Our world is filled with optical fibers carrying information across the room or around the world at rates of up to 25.6 terabits per second [1]. This astounding capacity is the result of about 40 years of development. An integral part of this was the accompanying measurements for characterizing optical fiber and its supporting components. Here we describe some of the optical fiber metrology measurement lessons learned from the telecommunications industry, with the goal of identifying applications for aerospace. We limit our discussion to single-mode fiber issues.

It seems that early in the process of fiber optic development, methods for characterization and specification were under-valued [2]. As the industry grew, ambitious goals necessitated accurate techniques for fiber characterization. Accurate measurements are not just about assessing and improving performance of the components, but also are required for interoperability between many different manufacturers and users. Through trial and error, a pattern emerged for successful measurement development. This four-step process involved the manufacturers, researchers and various standards bodies (IEC, TIA, ISO, and ITU) and is outlined below.

1. **Define the parameter and its required specification.** For example, low loss connections need accurate fiber alignment, requiring that fiber cladding diameter be specified to within 1 μm for splice loss less than 5 %. This in turn requires 0.1 μm of measurement accuracy.
2. **Select and document measurement methods.** For a given measurement parameter, not all the possible measurement techniques produce the same result. Measurement techniques must be well-defined and based on a fundamentally verifiable approach. The Telecommunication Industry Association (TIA) facilitates this by producing voluntary standards documents known as fiber optic test procedures (FOTP).
3. **Demonstrate global measurement agreement through interlaboratory "round robin" comparison(s).** It can be very enlightening to conduct a measurement comparison where several users measure the same device and compare their results. Such comparisons reveal both the agreement between differing measurement techniques and the variations in similar techniques used at different laboratories.
4. **Implement means for improving measurement disagreement.** From the results above, a change in a measurement definition might be in order. Or a poor agreement between participants might indicate the need for development of a calibration artifact.

An example of the utility of this four-step process came in the case of mode-field diameter (MFD). The two main MFD measurement techniques had incompatibilities in their definitions. That is, for a certain class of fibers, the techniques yielded different results. This was illustrated during a round-robin comparison [3]. A modification of the measurement definition ("Petermann MFD") improved the agreement, as demonstrated in a subsequent round robin [4]. This historical and ongoing development of metrology for optical fiber telecommunications has left a legacy of measurement resources for the aerospace industry. The list of these telecommunications parameters can generally be divided into the three classes described below.

Laser sources and detectors: The best measure of data transmission performance is signal-to-noise ratio (SNR), and in the absence of nonlinear effects, the transmitted signal power determines the SNR. This sets up a critical need for accurate measurement of laser power, optical fiber and component link loss, and spectral transmission as well as detector responsivity. Laser and detector calibrations are most efficiently performed by measurements of absolute power referenced to well-calibrated detectors (NIST offers high-level calibrations referenced to a cryogenic radiometer [5]) and characterization of detector linearity.

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Time and frequency response of receivers is important, but at single-channel data rates of a few tens of gigahertz envisioned for aerospace, characterization is routine and well understood. Several useful diagnostic instruments such as optical time domain reflectometers (OTDR) and optical spectrum analyzers (OSA) are convenient and widely used for these types of measurements but present a more complicated calibration challenge in that their measurements consist of a combination of fundamental parameters (e.g., wavelength and power). Measurement of wavelength is vital for spectrally efficient telecommunications applications such as dense wavelength division multiplexing (DWDM), where the channel spacings can be as small as 25 GHz. Metrology at this level is accomplished by use of well characterized wavelength absorption references based on molecular gas absorption spectra [6].

Optical fiber geometry: For short link lengths, connection losses can be a significant fraction of the loss budget. Most problems are usually geometrical mismatches in the fiber or connectors. The relevant geometrical parameters are MFD, cladding diameter and noncircularity, core concentricity, fiber coating diameter, connector ferrule bore and outside diameter, connector core concentricity, connector polish angle and fiber offset. For example, a 0.05 dB loss between two fibers or connectors results from just a 10 % mismatch in their MFD. These parameters have been well characterized, and many are supported by round-robin comparisons, reference artifacts or well documented measurement procedures [7].

Optical propagation characteristics: Significant effort and resources have been devoted to the development of measurements and test procedures for propagation distortions, including dispersion (polarization-mode dispersion, or PMD, and chromatic dispersion) as well as nonlinear effects. But, the impact of these parameters is likely negligible in the short-range, narrow-bandwidth environments expected in aerospace applications, where typical fiber lengths will be less than 20 or 30 m. A rule of thumb for dispersion impact is that the pulse spreading be less than one bit period. For chromatic dispersion, this sets the maximum data rate $f_B = \sqrt{c \cdot 10^3 / D\lambda^2 L}$, which for a dispersion-unshifted fiber operating at 1550 nm (dispersion coefficient D=17 ps/(nm·km)) yields the maximum data rate of almost 500 GB/s in a single channel. PMD in such short lengths of single-mode fiber will certainly be negligible. However, the coupling between the PMD in the fiber and the presence of polarization-dependent losses (PDL) in the system can produce transmission loss that varies with time or environmental changes. And, because it is a statistical quantity relying on comparisons of absolute powers, PDL can be tricky to measure. Measurement prescriptions have been well-documented [8]. Nonlinear effects in fibers depend on peak power, propagation distance, modulation format, etc. But given the short propagation distances in avionic applications, there is no need for powers high enough to approach the nonlinear regime, and nonlinear effects will not be a concern.

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