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Bibliography of NIST Publications on Multimode Optical Fibers

Edited by

Sara Metz
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U.S. DEPARTMENT OF COMMERCE, William M. Daley, Secretary
TECHNOLOGY ADMINISTRATION, Gary R. Bachula, Acting Under Secretary for Technology
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, Raymond G. Kammer, Director

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Introduction

Multimode optical fibers are staging a comeback, largely for use in local area networks, where their limited length-bandwidth product is not necessarily a drawback. At the same time, a generation of engineers has grown up with single-mode fibers and relatively limited knowledge of multimode fibers. Many of the measurement problems that face users of multimode fibers, however, are identical to those that were encountered 20 years ago. Some of these problems were solved by standardized launching conditions, whereas others were never completely resolved. Other problems arise anew because laser diodes capable of exciting small mode volumes are expected to permit higher bandwidth.

The purpose of this Interagency Report is to familiarize today's engineers with earlier NIST work on the metrology of multimode fibers and related components. Much of this work was carried out in collaboration with the Electronic Industries Association or its offshoot, the Telecommunications Industry Association. This work has been described in a fairly large body of work by NIST authors, sometimes in collaboration with colleagues from industry. Many of the experiments described in the resulting publications led directly to interlaboratory intercomparisons and ultimately to voluntary standards, or Fiber Optic Test Procedures, for attenuation, bandwidth, index profile, and other parameters. The intercomparisons give a measure of the repeatability that might be expected with today's fibers and possibly obviate the need to perform similar intercomparisons again. The papers on attenuation and bandwidth, for example, show the rationale for adopting specific launching conditions; changing these launching conditions to fit specific applications may well pay off, but more work is needed to confirm such expectations.

What follows is a listing of the papers and reports published by the Optoelectronics Division of NIST and its predecessor, the Electromagnetic Technology Division. The list is restricted to publications that concern multimode fibers. We thought that reprinting the papers themselves would be extravagant and finally decided against selective reprinting as well. Instead, we have reproduced the titles and bibliographic data, and the abstracts of every division publication that related specifically to multimode fibers. Many but not all of the publications may still be available from the authors of those publications. Journal articles may be found in almost any science or engineering library. In-house publications such as Technical Notes and Interagency Reports may be obtained from the Government Printing Office or the National Technical Information Service, as detailed below.

The Optoelectronics Division was established in 1994 to provide the optoelectronics industry with measurement technology, standards, and traceability. The division maintains close connections to the optoelectronics industry. Division staff members represent NIST and the U.S. to the major domestic and international standards organizations active in optoelectronics–the Telecommunications Industry Association (TIA), the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the American National Standards Institute (ANSI)–and provide impartial technical expertise in their negotiations. The division typically has several active Cooperative Research and Development Agreements (CRADAs) with companies and universities, and is involved in 20 to 30 additional informal collaborations each year. The division offers the optoelectronics community an annual short course on laser measurements and biennially the *Symposium on Optical Fiber Measurements*, a major international conference on metrology for optical communications. The Fiber Optic Metrology project develops measurement methods and Standard Reference Materials for optical fibers, and interacts with standards groups to provide a metrology base for the lightwave communication industry.

Optical fibers have largely replaced coaxial cable in long-distance telecommunications systems and are rapidly being installed in local-area applications. NIST staff interact with industry groups to develop measurement methods and reference standards for the characterization of these components. Connecting optical fibers requires the fibers to have accurately controlled dimensions. NIST-developed Standard Reference Materials for cladding diameter allow manufacturers to calibrate instrumentation used in manufacturing and quality control; geometrical standards for fiber coatings and connector ferrules are being developed as well. Dispersion, the variation of propagation velocity with wavelength or polarization, sets the limit to the rate at which information can be transmitted; measurement methods and standards for both chromatic dispersion and polarization-mode dispersion are either available or under development. The development of optical amplifiers has brought revolutionary changes to the design of communications; these new components require special methods of characterization now in development. Nonlinear properties of fiber, such as four-wave mixing and soliton effects, have been studied and applied to instrumentation. Novel implementations of reflectometry in fiber are also studied.

We are indebted to Annie Smith for *A Bibliography of the NIST Optoelectronics Division* and to Douglas Franzen for his help and encouragement.

Anthologies

Optical Fiber Characterization: Attenuation, Frequency Domain Bandwidth and Radiation Patterns
G.E. Chamberlain, G.W. Day, D.L. Franzen, R.L. Gallawa, E.M. Kim, M. Young
National Bureau of Standards Special Publication 637, vol. 2, 235 pp.; October 1983

This is the second volume of a series intended to describe optical fiber measurement systems developed at the National Bureau of Standards. The topics covered in this volume are attenuation, bandwidth (frequency domain), and far-field and near-field radiation patterns. Each chapter includes a tutorial section and a detailed description of the apparatus. The volume concludes with a glossary of optical communications terms.

Keywords: Attenuation, bandwidth, core diameter, far field, measurements, near field, optical fiber

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Optical Fiber Characterization: Backscatter, Time Domain Bandwidth, Refracted Near Field, and Interlaboratory Comparisons
B.L. Danielson, G.W. Day, D.L. Franzen, E.M. Kim, M. Young
National Bureau of Standards Special Publication 637, vol. 1, 201 pp.; July 1982

Optical fiber waveguide measurements are described. Systems to determine the backscatter, bandwidth, and index profile are covered in detail. Measurement comparisons between laboratories are given for fiber attenuation, bandwidth, numerical aperture, and core diameter.

Keywords: Attenuation, backscatter, bandwidth, index profile, measurements, optical fiber

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*<u>Editors' note:</u> *The chapters in these volumes are reprints, sometimes revised and expanded, of earlier NBS Technical Notes and other publications. For abstracts or copies of a specific chapter in its original form, please refer to its independent citation elsewhere in this document.*

The Characterization of Optical Fiber Waveguides: A Bibliography with Abstracts, 1970-1980
G.W. Day, editor
National Bureau of Standards Technical Note 1043, 65 pp.; June 1981

This bibliography contains approximately 450 citations of papers concerning the characterization of optical fiber waveguides. Papers from scientific journals, trade journals and conferences are included along with book chapters. The citations are organized by parameter measured and measurement method. Where published abstracts are available they are included.

Keywords: Bibliography, measurements, optical fibers, optical communications

Technical Digest, Symposium on Optical Fiber Measurements, 1996
G.W. Day, D.L. Franzen, P.A. Williams, editors
National Institute of Standards and Technology Special Publication 905, 215 pp.; September 1996

Technical Digest, Symposium on Optical Fiber Measurements, 1994
G.W. Day, D.L. Franzen, R.K. Hickernell, editors
National Institute of Standards and Technology Special Publication 864, 219 pp.; September 1994

Technical Digest, Symposium on Optical Fiber Measurements, 1992
G.W. Day, D.L. Franzen, editors
National Institute of Standards and Technology Special Publication 839, 238 pp.; September 1992

Technical Digest, Symposium on Optical Fiber Measurements, 1990
G.W. Day, D.L. Franzen, editors
National Institute of Standards and Technology Special Publication 792, 201 pp.; September 1990

Technical Digest, Symposium of Optical Fiber Measurements, 1988
G.W. Day, D.L. Franzen, editors
National Bureau of Standards Special Publication 748, 193 pp.; September 1988

Technical Digest, Symposium on Optical Fiber Measurements, 1986
G.W. Day, D.L. Franzen, editors
National Bureau of Standards Special Publication 720, 150 pp.; September 1986

Technical Digest, Symposium on Optical Fiber Measurements, 1984
G.W. Day, D.L. Franzen, editors
National Bureau of Standards Special Publication 683, 140 pp.; September 1984

Technical Digest, Symposium on Optical Fiber Measurements, 1982
G.W. Day, D.L. Franzen, editors
National Bureau of Standards Special Publication 641, 148 pp.; September 1982

Technical Digest, Symposium on Optical Fiber Measurements, 1980
G.W. Day, D.L. Franzen, editors
National Bureau of Standards Special Publication 597, 146 pp.; September 1980

Attenuation

Measurement of Multimode Optical Fiber Attenuation: An NBS Special Test Service
R.L. Gallawa, G.E. Chamberlain, G.W. Day, D.L. Franzen, M. Young
National Bureau of Standards Interagency Report 83-1691, 26 pp.; February 1984

This document is one of a series that describes optical fiber measurement procedures and capabilities at the National Bureau of Standards (NBS). We concentrate here on the measurement of attenuation of multimode, telecommunication-grade fibers for the wavelength range of 850 nm to 1300 nm. The document gives details on the measurement procedure, which is based on the Electronic Industries Association Recommended Standard as published in RS 455. The procedure is based on two restricted launch conditions, either of which may be used to control the modal power distribution at launch. The intent is to approximate the conditions that exist in a long link, to the end that the reported attenuation coefficient is indicative of what can be expected in long, concatenated links.

Keywords: Attenuation, fiber attenuation, fiber characterization, measurement, measurement techniques, optical fibers, optical waveguides

Measurement of Multimode Optical Fiber Attenuation
R.L. Gallawa, G.E. Chamberlain, G.W. Day, D.L. Franzen, M. Young
National Bureau of Standards Technical Note 1060, 47 pp.; June 1983

This document is one of a series which describes optical fiber measurement capabilities at the National Bureau of Standards. We concentrate here on the measurement of attenuation of multimode, telecommunication-grade fibers for the wavelength range of 850 nm to 1300 nm. The document begins by discussing the need for restricted launch conditions, the most fundamental and crucial aspect of precise attenuation measurements. The limited phase space launch (also called the beam optics launch) and the mode filter launch are discussed. Attention then turns to the practical matter of ensuring that the conditions of the restricted launch are met. Discussions of system noise and system linearity are also included. The document describes measurement procedure and results obtained in the laboratory using three typical fibers. Results are presented for the two wavelengths of current interest: 850 nm and 1300 nm. The procedures are applicable to any wavelength, however. The document touches briefly on the matter of monomode fibers. Finally, a summary of the results from an interlaboratory comparison are presented to give perspective to the stability of a fiber subjected to handling and shipping.

Keywords: Attenuation, attenuation measurement, fiber measurement, optical fibers, optical waveguides

Core Diameter and Index Profile

Numerical Aperture of Multimode Fibers by Several Methods: Resolving Differences
D.L Franzen, M. Young, A.H. Cherin[*], E.D. Head[†], M.J. Hackert, K.W. Raine[‡], J.G.N. Baines[‡]
Journal of Lightwave Technology, vol. 7, no. 6, pp. 896-901; June 1989

An industry-wide study among members of the Electronic Industries Association was conducted to document differences among three numerical aperture measurement methods. Results on 12 multimode graded index fibers indicate systematic differences exist among commonly used far-field and index profile techniques. Differences can be explained

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by a wavelength dependent factor and choice of definitions. Conversion factors may be used to relate the various methods.

Profile Inhomogenity in Multimode Graded-Index Fibers
C.W. Oates, M. Young
Journal of Lightwave Technology, vol. 7, no.3, pp. 530-532; March 1989

We have measured the profile parameters (g) of several multimode graded index fibers and found that g may vary azimuthally by ±0.15 or more in fibers for which the average value is between 1.8 and 2.2.

Measurement of the Core Diameter of Graded-Index Optical Fibers: An Interlaboratory Comparison
E.M. Kim, D.L. Franzen
Applied Optics, vol. 21, no. 19, pp. 3443-3450; October 1, 1982

An interlaboratory measurement comparison of optical fiber-core diameter was conducted by the National Bureau of Standards (NBS) in cooperation with the Electronics Industries Association. Participants include NBS and three fiber manufacturers. Six graded-index fibers were measured by all participants using the transmitted near-field method. As a group, the transmitted near-field measurements were consistent and exhibited an average standard deviation of 0.5 μm for 50-μm core fibers. These results were also compared to diameters determined by refracted near-field and transverse interference measurements contributed by other laboratories. For smooth-index profiles, all three methods agree within ~1 μm; substantial differences between the transmitted near-field and the other two methods can exist for fibers having step structure near the core-cladding boundary.

Two Dimensional Near-Field Contouring of Optical Fiber Cores
E.M. Kim, D.L. Franzen
Proceedings of SPIE, vol. 355, Fiber Optics: Short-Haul and Long-Haul Measurements and Applications, pp. 76-83; 1982

A microcomputer controlled system is described for measuring the two dimensional near-field radiation pattern from optical fibers. Because radiation measurements may be made in two dimensions, a novel method has been devised whereby a constant intensity contour of the core is mapped. A modified Left-Most-Looking (LML) digital image encoding algorithm is used to map the contour of the fiber core. The iso-intensity map provides information about the tolerance field, in which all of the measured iso-intensity points lie, and core noncircularity. Such information is useful in determining coupling efficiency at splices, connector joints, and terminal points. This paper will discuss the measurement apparatus, accuracy, precision, stability, and method of analysis of the NBS system. In addition, results will be presented on measurements of core diameters, and length dependence of such measurements, wavelength dependence of the radiation patterns, power law fits to the patterns, calibration apparatus, and iso-intensity contours of telecommunications-grade fibers.

Optical Fiber Index Profiles by the Refracted-Ray Method (Refracted Near-Field Scanning)
M. Young
Applied Optics, vol. 20, no. 19, pp. 3415-3422; October 1, 1981

This paper has two primary purposes. First, it provides an elementary description and tutorial overview of the refracted-ray method of measuring fiber index profiles. Second, it presents new results concerning the theoretical foundation, the linearity and precision, and other aspects of the method. In particular, we find that index differences may be measured to 5% or better and conclude by showing ~3% agreement with another laboratory and good agreement with numerical aperture measurements performed by participants in an interlaboratory comparison.

Refracted-Ray Scanning (Refracted Near-Field Scanning) for Measuring Index Profiles of Optical Fibers
M. Young
National Bureau of Standards Technical Note 1038, 50 pp.; May 1981

The purpose of this work is twofold. First, it provides an elementary description and tutorial overview of the new refracted-ray method of measuring fiber-index profiles. Second, it presents new results concerning the theoretical foundations, the linearity and precision, resolution limit and edge response, and other aspects of the method. In particular, we find that index differences may be measured to 5 percent or better and spatial resolution is diffraction limited. We conclude by showing about 3 percent agreement with another laboratory and good agreement with numerical-aperture measurements performed by participants in a round-robin experiment.

Keywords: Fiber index profile, index profile, near-field scanning, optical communications, optical fiber, optical waveguide, refracted near-field scanning, refracted-ray scanning, resolution limit

Measurement of Far-Field and Near-Field Radiation Patterns from Optical Fibers
E.M. Kim and D.L. Franzen
National Bureau of Standards Technical Note 1032, 41 pp.; February 1981

Systems are described for measuring the far- and near-field radiation patterns from optical fibers. Parameters which affect measurement precision, accuracy, resolution, and signal-to-noise ratio are discussed. Measurements utilizing radiation patterns are covered; this includes radiation angle (numerical aperture), attenuation using mode filters, index profile, core diameter, and mode volume transfer function. Experimental examples are given in many instances.

Keywords: Attenuation, core diameter, far field, index profile, mode filter, numerical aperture, radiation angle, radiation patterns

Linearity and Resolution of Refracted Near-Field Scanning Technique
M. Young
Technical Digest, Symposium on Optical Fiber Measurements; National Bureau of Standards Special Publication 597, pp. 37-40; October 1980

Refracted near-field scanning is an attractive method for precisely determining the index profile of an optical waveguide. This method was first proposed and demonstrated by Stewart and later refined by White. In an earlier paper, I analyzed the linearity and precision of this method; this paper additionally discusses resolution and related areas.

Calibration Technique for Refracted Near-Field Scanning of Optical Fibers
M. Young
Applied Optics, vol. 19, no. 15, pp. 2479-2480; August 1, 1980

This paper describes a method for calibrating and determining the linearity of the refracted near-field scanning technique for measuring the index profile of optical waveguides. The method relies on a quartz fiber and several fluids whose indices are known at the measurement wavelength of 633 nm. The results show that near-field scanning is linear and that index profile may be measured to a precision of $\pm$ 0.0005 or better.

Dispersion and Bandwidth

Differential Mode Delay Measurements in Multimode Fibers using a Frequency Domain Technique with Variable Launch
D.L. Franzen, S.E. Mechels, J.B. Schlager
Proceedings of the 4th Optical Fiber Measurements Conference, edited by the National Physical Laboratory in cooperation with European Action COST 241, 1997, to be published.

Differential mode delay (DMD) profiles are determined for multimode fibers using a frequency domain phase shift technique. A time resolution of 0.2 ps is achieved making measurements on short lengths of fiber possible; comparisons with more traditional time domain methods on longer lengths show agreement. DMD profiles obtained on several 62 μm diameter core fibers exhibit a diverse range of behavior.

High Resolution Differential Mode Delay and Bandwidth in Multimode Fibers
J.B. Schlager, S.E. Mechels, D.L. Franzen
Proceedings of the IEEE Lasers and Electro-Optics Society 1997 Annual Meeting (LEOS '97), 1997, to be published.

Differential mode delay measurements in multimode fibers are performed using a frequency domain phase shift technique capable of 0.2 ps temporal resolution. Measurements give insight into the behavior of fiber bandwidth with respect to launching conditions.

High-Resolution Differential-Mode Delay Measurements in Optical Fibers Using a Frequency-Domain Phase-Shift Technique
S.E. Mechels, J.B. Schlager, D.L Franzen
IEEE Photonics Technology Letters, vol. 9, no. 6, pp. 794-796; June 1997

A frequency-domain phase-shift technique, with a temporal resolution of 0.2 ps, is used to obtain differential mode delay measurements in graded-index multimode fibers. This resolution is a significant improvement over previously reported time-domain methods. As a consequence, useful results can be obtained from fibers as short as 15 m. Measurements performed at 850 nm, on 62.5-μm core diameter fibers from several different manufacturers, indicate a rich variety of mode delay profiles. Measurements on lengths ranging from 3 to 500 m, indicate that delay profiles are established in the first few meters of fiber, and the general characteristics are retained over long distances.

Keywords: Optical fiber communication, optical fiber dispersion, optical fiber measurements, optical fibers, optical fiber testing.

Fiber Bandwidth Measurement Using Pulse Spectrum Analysis
Y. Shao, R.L. Gallawa
Applied Optics, vol. 25, no. 7, pp. 1069-1071; April 1, 1986

The pulse spectrum analysis (PSA) method of measuring fiber bandwidth has been suggested as an alternative to the frequency and time domain methods, but there is a paucity of information on the technique and very little data. In fact, we know of no measurement comparisons between the

PSA method and the frequency and time domain methods. The PSA method has the advantage of being very simple and gives results that are consistent with the time domain and frequency domain methods. The International Electrotechnical Commission (IEC) recommends the PSA method, but the Electronic Industries Association (EIA) of the U.S.A. takes no position in this regard. This paper gives results of an experiment which compared the three methods.

The Bandwidth of a Multimode Fiber Chain
P.M. Rodhe
Journal of Lightwave Technology, vol. LT-3, no. 1, pp. 145-154; February 1985

We propose a new method for evaluating the baseband transmission in a multimode fiber chain. Carnevale and Paek (*Bell Syst. Tech. J.*, vol. 62, pp. 1415-1431, 1983) stated that errors in the fiber manufacturing process will randomly distort a desired index profile, presumably of power-law type. We extend their discussion to the bandwidths of concatenated fibers, by considering Gaussian approximations to actual transfer functions. The bandwidth can thus be separated into two parts, one of which is due to the over- and undercompensation of individual, idealized power-law profiles and the other of which refers to random profile distortions as well as possible mode coupling within mode groups. The former part should normally dominate the length dependence of longer chains. The latter part may be replaced by an expectation value, typical for the actual manufacturing process. A remarkably good agreement is achieved between experimental and predicted bandwidths for various chain configurations.

Intramodal Part of the Transfer Function for an Optical Fiber
P.M. Rodhe
Journal of Lightwave Technology, vol. LT-3, no. 1, pp. 154-158; February 1985

Intramodal contributions in measurements of optical-fiber bandwidth are investigated theoretically and experimentally in the quasimonochromatic case. A relation is established between the intramodal transfer function and a possibly non-Gaussian source spectrum, which may also vary with modulation frequency. By considering the latter variation in particular, we are able to predict the intramodal length dependence and show how it may deviate from that of a conventional approach.

Pulse Spectrum Analysis Method of Measuring Fiber Bandwidth
S. Yang, R. Alvarez, C. Weimer, R.L. Gallawa
Proceedings of SPIE, vol. 559, pp. 207-210; 1985

A system for measuring optical fiber bandwidth utilizing the Pulse Spectrum Analysis method (PSA) has been established. This paper will discuss problems inherent to that system such as signal-to-noise ration and off-peak error. Included are the results of bandwidth measurements on multimode telecommunication grade fibers. Finally, the PSA method is compared to other bandwidth measurement methods: the frequency domain (FD) and the time domain (TD) methods.

Measurement of Optical Fiber Bandwidth in the Frequency Domain
G.W. Day
National Bureau of Standards Technical Note 1046, 41 pp.; September 1981

The design, evaluation, and performance of a system for determining the magnitude of the transfer function (hence, the bandwidth) of a multimode optical fiber are presented. The system operates to about 1450 MHz using a tracking generator/spectrum analyzer combination for narrowband detection. It is constructed, almost entirely, from commercially available components. The system is less complex and easier to use than an equivalent time domain system and the measurement precision is comparable. Background information on time and frequency domain specifications, fiber bandwidth limitations, and alternate frequency domain techniques is also presented.

Keywords: Fiber optics, optical communications, optical fiber bandwidth, optical fiber distortion, optical fibers

Measurement of Optical Fiber Bandwidth in the Time Domain
D.L. Franzen, G.W. Day
National Bureau of Standards Technical Note 1019, 66 pp.; February 1980

A system is described for determining optical fiber bandwidth from time domain information. A measurement gives the optical fiber transfer function (or frequency response) relating the output waveform to the input. An analysis is given of the variables affecting the measurement. This includes a discussion of such input related topics as launching conditions, mode scramblers, and laser diode sources; output related topics include a discussion of optical detectors. Laser diodes are evaluated with respect to short pulse performance, near field emission, material dispersion limits, and other spectral behavior like chirping; detectors are evaluated with respect to time response, linearity, and uniformity. Overall system architecture, precision, and dynamic range are discussed. A number of bandwidth related topics are briefly presented and typical experimental results given. This includes examples of: mode mixing via microbending, profile compensation, profile dispersion, intramodal broadening, material dispersion constants, relative magnitude-phase behavior, and Gaussian predictions of frequency response.

Keywords: Bandwidth, laser diodes, material dispersion, mode scramblers, optical detectors, optical fibers, transfer function

Measurement of Propagation Constants Related to Material Properties In High-Bandwidth Optical Fibers

D.L. Franzen, G.W. Day

IEEE Journal of Quantum Electronics, vol. QE-15, no. 12, pp. 1409-1414; December 1979

The material contribution to group index and material dispersion were measured in high-bandwidth graded-index optical fibers. A shuttle-pulse technique provided measurements of group index with precisions and accuracies of 0.1 and 0.2 percent using 5 m lengths of optical fiber. Material dispersion in fibers was measured over the 0.8-0.9 μm wavelength region using different wavelength, short-pulse laser diodes. The influence of material dispersion on fiber bandwidth measurements was evaluated for laser diode sources. Limitations arising from source linewidth were experimentally determined from measurements on a fiber with high microbending enhanced bandwidth.

Limitations Imposed by Material Dispersion on the Measurement of Optical Fiber Bandwidth with Laser Diode Sources

D.L. Franzen, G.W. Day

Journal of the Optical Society of America, vol. 69, no. 10, pp. 1448; October 1979

Contributions to the fiber bandwidth arising from material dispersion and finite source linewidth must be evaluated in order to document measurement systems. In order to specify the bandwidth resulting from only differential mode delays, the material dispersion component must be deconvolved or made negligible; otherwise, the measured bandwidth would depend on the source linewidth. Material dispersion constants were measured for several commercial, graded index fibers over the 0.8 to 0.9-μm region, and spectral lineshapes were determined for a number of SHJ laser diodes. Due to the complexity of lineshapes and occasional chirping behavior, it seems unlikely that a bandwidth correction term can be calculated with a high degree of certainty. A more prudent approach is to place an upper limit on bandwidth that can be measured with a particular diode. For bandwidths below a certain maximum bandwidth f_m the material dispersion contribution would be less than 6% of the measured bandwidth. For SHJ laser diodes producing 260-ps full width at half maximum (FWHM) pulses, this limit f_m depends upon the specific diode and is in the 1-2 GHz km range. The upper bandwidth limit was also experimentally determined by measurements on a graded index fiber with a high (5 GHz km) microbending enhanced bandwidth.

Time Domain Pulse Measurements and Computed Frequency Responses of Optical Communications Components
J.R. Andrews, M. Young
National Bureau of Standards Interagency Report 79-1620, 32 pp.; September 1979

The purpose of this report is to demonstrate the application of the NBS Automatic Pulse Measurement System (APMS) to measuring the pulse responses of optical communications components and to computing their impulse and frequency responses. For example we describe measurements of the properties of two glass fibers and an avalanche photodiode using both a pulsed GaAs laser diode (λ = 0.9 µm) and a mode locked, Nd:YAG laser (λ= 1.06 µm). All measurements were performed in the time domain; frequency domain data were obtained from the time domain data by using the Fast Fourier Transform (FFT). The impulse response was obtained by deconvolution.

Keywords: Avalanche photodiode, FFT, fiber optics, frequency response, impulse response, laser, photodiode

Interlaboratory Comparisons

Optical Fiber Measurements: Results of Interlaboratory Evaluations
D.L. Franzen
Proceedings of SPIE, vol. 992, pp. 242-244; September 1988

Results of industry-wide round robin comparisons administered by the National Bureau of Standards and the Electronic Industries Association are presented. Multimode fiber parameters include attenuation, bandwidth, core diameter, and numerical aperture. Single-mode fiber parameters include cut-off wavelength and mode-field diameter.

An Electronic Industries Association Interlaboratory Comparison to Resolve Differences in Multimode Fiber Numerical Aperture Measurements
A.H. Cherin*, E.D. Head*, D.L. Franzen, M. Young, M. Hackert†
Technical Digest, Symposium on Optical Fiber Measurements, 1988; National Bureau of Standards Special Publication 748, pp. 157-159; G.W. Day and D.L. Franzen, eds.; 1988

An industry-wide study among members of the Electronic Industries Association (EIA) was conducted to document and reconcile differences between various numerical aperture (*NA*) definitions and measurement

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†Corning Glass Works, Corning, NY 14831

methods. Results on twelve multimode graded index fibers indicate that systematic differences exist among commonly used far-field and index profile techniques. The differences can be explained by a wavelength dependent factor and the choice of *NA* definitions. Conversion factors have been developed to relate the various measurement methods and definitions.

Interlaboratory Measurement Comparison to Determine the Attenuation and Bandwidth of Graded-Index Optical Fibers
D.L. Franzen, G.W. Day, B.L. Danielson, G.E. Chamberlain, E.M. Kim
Applied Optics, vol. 20, no. 14, pp. 2412-2419; July 15, 1981

An interlaboratory measurement comparison was conducted by the National Bureau of Standards in cooperation with the Electronic Industries Association. Participants included NBS and nine optical fiber and cable manufacturers. Four graded-index fibers having lengths of 2, 2, 2, and 0.9 km were used. Measurements of attenuation at 850 nm, using both beam optics and mode filter approaches to achieve a restricted launch, gave one standard deviation spreads of 0.24, 0.12, 0.12, and 0.43 dB/km for an overall average of 0.23 dB/km. Best measurement agreement was obtained for a fiber having little differential mode attenuation. Measurements of –3-dB bandwidth from time domain acquired data at 90 nm gave an average on standard deviation spread of 12% with poorer agreement on the higher frequency portion of the frequency response.

Interlaboratory Measurement Comparison to Determine the Radiation Angle (N.A.) of Graded-Index Optical Fibers
D.L. Franzen, E.M. Kim
Applied Optics, vol. 20, no. 7, pp. 1218-1220; April 1, 1981

A procedure for determining the radiation angle (N.A.) of graded-index optical fibers was tested by an interlaboratory measurement comparison among six fiber manufacturers and the National Bureau of Standards (NBS). Radiation angle was determined using the 5% intensity points on an exit far-field radiation pattern. Measurements on fibers representing low-to-high N.A. values show standard deviations of 2.9, 2.4, 2.0, 1.5, and 0.9%. The overall average, 2.0%, is close to the one standard deviation measurement precision reported by most participants.

Results of an Interlaboratory Measurement Comparison Among Fiber Manufacturers to Determine Attenuation, Bandwidth, and N.A. of Graded-Index Optical Fibers.
D.L. Franzen, G.W. Day, B.L. Danielson, E.M. Kim, G.E. Chamberlain
Digest, 3rd International Conference on Integrated Optics and Optical Fiber Communications, pp. 74-75; April 1981

An interlaboratory measurement comparison to determine optical fiber attenuation, bandwidth, and N.A. was conducted by the National Bureau of Standards (NBS II). Participants include several U.S. fiber and cable manufacturers, one Canadian manufacturer, and NBS. The purpose of the comparison is to gather information on measurements when participants follow the same procedures. The procedures used for attenuation and N.A. are currently pending before the Electronic Industries Association Committee P6.6.

Attenuation Measurements on Optical Fiber Waveguides: An Interlaboratory Comparison among Manufacturers
G.W. Day, G.E. Chamberlain
National Bureau of Standards Interagency Report 79-1068, 32 pp.; May 1979

In late 1978, the National Bureau of Standards invited U.S. manufacturers of optical fiber waveguide to participate in an interlaboratory comparison of attenuation measurements. Seven manufacturers performed four different measurements on each of two fibers. The range of results was typically 1 to 1.5 dB/km for fiber with 3 to 7 dB/km nominal attenuation. This report contains the results and an analysis based on additional data taken by NBS.

Keywords: Attenuation, fiber optics, interlaboratory comparison, measurements, optical communications, quality control

Miscellaneous and Reviews

Transfer Functions for Characterizing Multimode Optical Fiber Components
S. Yang
National Institute of Standards and Technology Interagency Report 3997, 132 pp.; January 1993

A mode transfer function approach is proposed to characterize optical fiber devices. The transfer function is used to analyze the accuracy of the mode transfer matrix, which is currently being used to characterize optical fiber devices. The analysis shows that the mode transfer matrix depends on launch condition. Based on the study of the physical process of two basic mode coupling mechanisms, that is, the scattering coupling and the overlap coupling, two basic transfer functions are derived. Mode transfer functions for fibers/cables, connectors/splicers, and power splitters are formed using these two basic transfer functions. Results of a round-robin test and a concatenation experiment show that the transfer function is better than the transfer matrix in that it is independent of launch conditions, and thus can improve both the repeatability of measurements made by different laboratories and the prediction of concatenated results. The transfer function can also be used to analyze the structure of a device.

Keywords: Fiber optics, mode coupling, multimode fibers, optical fiber devices, transfer function, transfer matrix

Optics and Lasers, including Fibers and Optical Waveguides, 4th Edition; Chaps. 10, 11.
M. Young
Springer-Verlag, Berlin, Heidelberg, 1992

Chapter 10 introduces optical fiber waveguides, graded-index fibers, and connectors, using primarily a descriptive, ray-optics approach. Chapter 11 introduces restrictive launching conditions and applies them to measurements of the attenuation and bandwidth of multimode fibers. It goes on to discuss optical time-domain reflectometry, index profile measurements, and numerical aperture measurements.

Modified Airy Function and WKB Solutions to the Wave Equation
A.K. Ghatak, R.L. Gallawa, I.C. Goyal
National Institute of Standards and Technology Monograph 176, 165 pp.; November 1991

The purpose of this monograph is to revisit a basic equation of mathematical physics,

$$\frac{d^2\Psi}{dx^2} + \Gamma^2(x)\Psi(x) = 0 \qquad (1)$$

and to give approximate solutions based on the *WKB* method and on a modification of the Airy function. All of the examples that we will use to illustrate the methods are based on optical waveguides and quantum mechanical problems. We hope that this monograph will prove to be a tutorial, giving insight and understanding to the use of Airy functions in addressing the scalar wave equation.

A Single Launch Technique for Determination of Mode Transfer Matrices
S. Yang, D.R. Hjelme, I.P. Januar, I.P. Vayshenker, A.R. Mickelson
Technical Digest, Symposium on Optical Fiber Measurements 1988; National Bureau of Standards Special Publication 748, G.W. Day, D.L. Franzen, ed., 193 pp.; September 1988

We derive a simple model for for the mode transfer function of low-loss components. We measured this transfer function and used it to calculate the transfer matrixes of the component. This method requires only a single launch and avoids submicrometer scanning. In addition, the tranfer function contains more information about a component than any of its associated transfer matrixes.

Standardizing Test Conditions for Characterizing Fibers
D.L. Franzen, G.W. Day, R.L. Gallawa
Laser Focus, pp. 103-105; August 1981

For different testing labs to come up with the same results for the same fibers, they all must use the same launch conditions. Here are some recommended procedures.

Measurement Problems in Multimode Optical Waveguides
G.W. Day
Proceedings, International Communications Conference, vol. 1; June 1978

This paper is primarily a review of problems associated with propagation measurements in multimode optical waveguides. Emphasis is placed on techniques which are of maximum use to the communication system designer.

Optical Time Domain Reflectometry

Group Index and Time Delay Measurements of a Standard Reference Fiber
B.L. Danielson, C.D. Whittenberg
National Bureau of Standards Interagency Report 88-3091, 16 pp.; July 1988

We describe measurement techniques for establishing a standard reference fiber with well characterized group index and time 01 group delay. Evaluation of an interferometric method indicates that fiber group index can be determined with a total estimated uncertainty of about 0.03 percent in small samples. Group delay of the reference fiber was measured with an overall uncertainty less than 0.004 percent in a 7 km waveguide. We discuss the application of a standard reference fiber to calibration of the distance of a standard reference fiber to calibration of the distance measurement accuracy of an optical time-domain reflectometer (OTDR).

Keywords: Calibration procedures, optical delay line, optical fiber group index, optical fiber group velocity, optical time-domain reflectometer, OTDR, standard reference fiber, standard test fiber

Calibration and Standardization Issues for the Optical Time-Domain Reflectometer
B.L. Danielson
National Bureau of Standards Interagency Report 87-3078, 10 pp.; December 1988

We review some of the issues related to the specification and assurance of optical time-domain reflectometer (OTDR) performance. These include selection of appropriate performance parameters, definition of terms, test procedures, measurement difficulties, and use of standard reference fibers. Some recommendations are given for an OTDR calibration program.

Keywords: Calibration procedures, optical time-domain reflectometer, OTDR, performance calibrations, standard reference fiber, standard test fiber, test procedures

Optical Time-Domain Reflectometer Specifications and Performance Testing
B.L. Danielson
Applied Optics, vol. 24, no. 15, pp. 2313-2322; August 1, 1985

From a researcher's as well as a user's point of view, it is highly desirable to adopt a common basis for specifying optical time-domain reflectometer performance parameters. This paper proposes some procedures and test methods which permit these devices to be characterized in a consistent way. Passive test fixtures are also described which may facilitate measurements of dynamic range and other reflectometer properties.

Optical Time-Domain Reflectometer Performance and Calibration Studies
B.L. Danielson
National Bureau of Standards Technical Note 1065, 26 pp.; June 1983

The measurement accuracy of the optical time-domain reflectometer (OTDR) is restricted in some applications by a limited operational dynamic range and by a lack of standardized test procedures. In an effort to better understand these restrictions, we have measured the range of linearity of some avalanche photodiodes used as backscatter detectors. Also, the effect of input launch conditions is examined and a possible standardized OTDR test procedure is proposed. Using these suggestions, we have made comparisons between attenuation values determined by cutback and backscatter methods and found that good agreement is possible. Finally, some methods are described for checking the response linearity of OTDR systems.

Keywords: APD, avalanche photodiodes, backscattering, backscatter signatures, optical fiber scattering, optical time-domain reflectometer, OTDR

Backscatter Signature Simulations
B.L. Danielson
National Bureau of Standards Technical Note 1050, 95 pp.; December 1981

This report presents a collection of computer-generated backscatter signatures which represent realistic replicas of signals that can be encountered in optical time-domain reflectometer (OTDR) systems. Emphasis is placed on illustrating the appearance of backscatter signatures originating from localized and distributed imperfections which are superimposed on an otherwise uniform optical fiber. The details of these signatures are shown to be a function of the particular type of fiber perturbation, experimental parameters, and data reduction methods. This compilation of simulated responses is intended to facilitate the correct interpretation of OTDR signals as well as to point out sources of error which can arise in the characterization of optical fibers using backscatter techniques.

Keywords: Backscattering, backscatter signatures, optical fiber scattering, optical time-domain reflectometer, OTDR

Backscatter Measurements on Optical Fibers
B.L. Danielson
National Bureau of Standards Technical Note 1034, 45 pp.; February 1981

An optical time domain reflectometer (OTDR) and its components are described in detail. The system performance for this device is examined. Experimental methods are described for the measurement of several parameters of interest in the characterization of optical fibers using the OTDR. These parameters include scattering loss and capture fractions for unperturbed fibers. Experimental capture-fraction values are reported for several step and graded-index fibers and these results are compared with theoretical predictions. Rayleigh backscatter signatures are also presented for several fibers from different manufacturers. Fault signatures are shown for some intrinsic and extrinsic fiber perturbations.

Keywords: Backscattering, capture fractions, fiber scattering, optical time domain reflectometry, Rayleigh scattering

An Assessment of the Backscatter Technique as a Means for Estimating Loss in Optical Waveguides
B.L. Danielson
National Bureau of Standards Technical Note 1018, 77 pp.; February 1980

This technical note addresses some of the problems associated with determining the accuracy of the backscatter technique as it is applied to the estimation of attenuation in optical waveguides. The basic theoretical assumptions involved in optical time domain reflectometry are reviewed; the effect on calculated loss values resulting from a departure from these assumptions is then examined. The approach taken is to employ computer modeling of the various scattering and other loss mechanisms using the bulk material properties of optical fibers. Computer responses permit a numerical comparison between the direct (insertion) method of measuring attenuation and several methods of estimating attenuation from analysis of backscatter data. Numerous examples are given of physical effects which can produce discrepancies in attenuation values calculated from backscatter signals. Also, some experimental comparisons are made between backscatter-derived and directly measured attenuation values in step and graded-index optical waveguides. Finally, the conditions necessary for good agreement between the direct and backscatter methods are discussed and suggestions for minimizing these errors are made.

Keywords: Backscattering, fiber attenuation, fiber loss, fiber scattering, optical time domain reflectometry, Rayleigh scattering

Glossaries

IEEE Standard Definitions of Terms Relating to Fiber Optics
Sponsored by the Fiber Optics Committee of the IEEE Communications Society
IEEE Standard 812-1984, 31 pp.; December 15, 1984

This document is based on the NTIA-SP-79-4 Optical Waveguide Communications Glossary, issued in September 1979 by the U.S. Department of Commerce; its updated version issued in the latter part of 1981; and the input from Project 812 Ad Hoc Working Group in April 1981. The contributors to the final document include A.G. Hanson, L.R. Bloom, R.L. Gallawa, E.M. Gray, G.W. Day, M. Young, A.H. Cherin, T.L. Gower, C.K. Kao, F.P. Kapron, B.S. Kawasaki, R.L. Lebduska, R.E. Love, P. Reitz, M. Kincaid, J.G. Nault, F. Sladen, J. Masterson, J. Fridman, D. Stone, and G.P. Kurpis.

The final draft (#2) of this document was accepted by the Fiber Optics Subcommittee of the Transmission Systems Committee of the IEEE Communications Society, and submitted to the IEEE Standards Board for approval. This project has been coordinated with the following outside organizations: SAE, ASTM, EIA and IEC.

Optical Waveguide Communications Glossary

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National Bureau of Standards Handbook 140, 27 pp.; January 1982

The rapid emergence of optical waveguide communications from the laboratory into commercial systems applications has been accompanied by the growth of a specialized vocabulary. Some terms have been borrowed freely from the disciplines of optical physics and communications engineering; others have been coined independently.

In this process, inevitably, some ambiguity and impreciseness have resulted. More significantly perhaps, some terms have been used to specify a product–and are beginning to be accepted by manufacturers and users–but are not precise <u>descriptors</u> beyond rather narrow limits. The absence of a precise, common language among researchers, manufacturers, systems designers, and users is a hindrance to effective technology development and utilization.

The goal of this glossary is to nurture such a language.

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