NBS Publications

NATIONAL BUREAU OF STANDARDS

NBS TECHNICAL NOTE 1043

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

The Characterization of Optical Fiber Waveguides

A Bibliography with Abstracts, 1970 - 1980

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress on March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau's technical work is performed by the National Measurement Laboratory, the National Engineering Laboratory, and the Institute for Computer Sciences and Technology.

THE NATIONAL MEASUREMENT LABORATORY provides the national system of physical and chemical and materials measurement; coordinates the system with measurement systems of other nations and furnishes essential services leading to accurate and uniform physical and chemical measurement throughout the Nation's scientific community, industry, and commerce; conducts materials research leading to improved methods of measurement, standards, and data on the properties of materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; develops, produces, and distributes Standard Reference Materials; and provides calibration services. The Laboratory consists of the following centers:

Absolute Physical Quantities[2] — Radiation Research — Thermodynamics and Molecular Science — Analytical Chemistry — Materials Science.

THE NATIONAL ENGINEERING LABORATORY provides technology and technical services to the public and private sectors to address national needs and to solve national problems; conducts research in engineering and applied science in support of these efforts; builds and maintains competence in the necessary disciplines required to carry out this research and technical service; develops engineering data and measurement capabilities; provides engineering measurement traceability services; develops test methods and proposes engineering standards and code changes; develops and proposes new engineering practices; and develops and improves mechanisms to transfer results of its research to the ultimate user. The Laboratory consists of the following centers:

Applied Mathematics — Electronics and Electrical Engineering[2] — Mechanical Engineering and Process Technology[2] — Building Technology — Fire Research — Consumer Product Technology — Field Methods.

THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides scientific and technical services to aid Federal agencies in the selection, acquisition, application, and use of computer technology to improve effectiveness and economy in Government operations in accordance with Public Law 89-306 (40 U.S.C. 759), relevant Executive Orders, and other directives; carries out this mission by managing the Federal Information Processing Standards Program, developing Federal ADP standards guidelines, and managing Federal participation in ADP voluntary standardization activities; provides scientific and technological advisory services and assistance to Federal agencies; and provides the technical foundation for computer-related policies of the Federal Government. The Institute consists of the following centers:

Programming Science and Technology — Computer Systems Engineering.

[1]Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted;
mailing address Washington, DC 20234.
[2]Some divisions within the center are located at Boulder, CO 80303.

The Characterization of Optical Fiber Waveguides

A Bibliography with Abstracts, 1970 - 1980

Edited by
G.W. Day

Electromagnetic Technology Division
National Engineering Laboratory
National Bureau of Standards
Boulder, Colorado 80303

NBS technical note

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

Issued June 1981

NATIONAL BUREAU OF STANDARDS TECHNICAL NOTE 1043

Nat. Bur. Stand. (U.S.), Tech. Note 1043, 72 pages (June 1981)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON 1981

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

Price $4.25 (Add 25 percent for other than U.S. mailing)

CONTENTS

The Characterization of Optical Fiber Waveguides
A Bibliography with Abstracts, 1970 - 1980

Edited by

G. W. Day
National Bureau of Standards
Boulder, CO 80303

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.

Key words: Bibliography, measurements, optical fibers, optical communications.

INTRODUCTION

Since the theoretical work of the mid-sixties and the experimental break-through of a decade ago, the literature of optical fiber communications has grown at an accelerating rate and is now vast. Examination of the 1980 subject index of the journal Applied Optics, for example, shows that "Fiber Optics" is by far the largest subject category and comprises several percent of the total content of the volume.

Specialists in optical communciations generally recognize that the characterization of the transmission medium, the fiber itself, is among the more challenging and important problems in the field. The published literature reflects an emphasis in this area as does the level of participation and attendance at conferences devoted specifically to the topic.* The growing interest in measurement standards observed by several national and international standards groups is another indication of the importance of the problem.

There are as yet no comprehensive books treating the subject of fiber measurements; neither are there many extended review articles. This places newcomers to the field, especially those who must quickly learn to specify components and design systems, at a particular disadvantage. The main purpose of this bibliography is to assist such individuals to identify and organize the published literature. It should also be useful as a guide and reference document to those more experienced.

The scope of this bibliography is limited to the optical properties of fiber and connecting devices. Mechanical characterizations are excluded except for the geometric parameters of the core and cladding because of their intimate relation to optical properties. Most of the papers deal rather specifically with measurement techniques. Some theoretical and analytical papers that directly support measurement techniques are also included.

The listings were compiled from several sources. The Engineering Index and Physics Abstracts were consulted as were the annual indices of journals in which papers on fiber measurements frequently appear. Lists of references from the more extensive review articles were another source. Papers from conferences are included whenever they contain substantial technical information and when the digest or proceedings is, in the editor's judgment, readily available.

The final product is a comprehensive but not exhaustive compilation of the literature. Numerous papers, some of which may be very important, have undoubtedly been overlooked. The editor begs the forgiveness of both the authors of those papers and the reader who may thus miss useful information.

*To date three such topical meetings have been held in different countries. They are as follows:
Symposium on Optical Fiber Measurements - 1980, Boulder, Digest published as NBS-SP-597 by the U.S. Govt. Printing Office.
Messtechnik in der optischen Nachrichtentechnik, Berlin, 1980, Digest published by VDE-Verlag GmgH.
Colloquium on Measurement Techniques for Optical Fibre Systems, London, 1979, Digest published by IEE.

The basic organization is by measurement parameter. When those categories are large they are subdivided by measurement method. Entries are in inverse chronological order by year and alphabetical order by author within a given year. There are no duplicate entries. The reader is therefore cautioned to look for specific material in all of the appropriate sections. Useful material on OTDR techniques, for example, could appear in sections 1.1, 1.2, 2.1, 2.3, and 5.3.

The citation format for journal articles follows fairly closely the ANSI standard using journal abbreviations recommended by the AIP:

Journal Abbreviation vol. #: inclusive pg. #s; year

Conference publications take the form:

Type of pub., Conf. Name, Location: inclusive pg. #s; year, Publisher

Book chapters take the form:

In "Book Title", Author or Editor, Publisher, year

Papers in languages other than English are indicated by the original language title followed by the translated title. English abstracts are included where available.

The editor is greatly indebted to Thinh Q. Sam for assuming much of the routine work of compiling this bibliography and to Victoria R. Schneller of the National Oceanic and Atmospheric Administration Library, Boulder, for assistance in the literature search.

1. GENERAL TOPICS

1.1 Review Papers

B. Costa and B. Sordo

Fibre characterization

In "Optical fibre communications", Technical Staff of CSELT, McGraw Hill, 1980

*****

P. L. Chu

Measurements in optical fibres

Proc. IREE Aust. 40:102-114; 1979

Various measurements of optical fibre characteristics are reviewed. These include measurements of attenuation, pulse distortion, fibre bandwidth, mode dependent attenuation, refractive index profile and fibre diameter. Emphasis is given to those methods which have not been reported in great detail in other review papers on similar topics.

*****

Leonard G. Cohen, Peter Kaiser, Paul D. Lazay, and Herman M. Presby

Fiber characterization

In "Optical fiber telecommunications", S. E. Miller and A. G. Chynoweth, eds., Academic Press, 1979

*****

Felix P. Kapron, K. Scott Gordon, and Francis M. E. Sladen

Measurement techniques for passive optical components

Conf. Rec., Int. Conf. Commun., Boston, 36.5.1-36.5.6; 1979, IEEE

Passive optical components in fiber communications systems include source-to-fiber couplers, the fiber, fiber-to-fiber joints, directional couplers, and wavelength-selective devices. This paper will consider the component specifications necessary for accurate systems design. Attenuation alone is insufficient to predict signal deterioration, but dispersion and often backscattering must also be taken into account.

Measurements suitable for the determination of the above specification parameters are presented along with numerous references. Generally, it is found that the performance of a passive component depends upon its location within a fiber link and upon the nature of the components it interfaces with. Passive device parameters are therefore both intrinsic and extrinsic, and specifications must necessarily include a description of measurement conditions - at least until such conditions are standardized within the industry.

*****

Carlo G. Someda

Experimental evaluation of optical fibers: A review

In "Fiber and Integrated Optics," D. B. Ostrowsky, ed., Plenum Press, 1979

*****

O. Krumpholz

Measuring parameters of fibres and fibre cables

Proc., Third Eur. Conf. Opt. Commun., Munich, 38-42; 1977

The most important parameters of an optical fibre waveguide are attenuation, numerical aperture, refractive index profile, core diameter, and pulse response or frequency basebandwidth. Various techniques to determine these characteristics have been evaluated and are discussed.

*****

Michael K. Barnoski and S. D. Personick

Measurements in fiber optics

Proc. IEEE 66:429-441; 1978

Recent advances in optical-fiber technology dictate that attention must be given to establishing accurate and precise measurement techniques. In this paper measurements currently employed to determine the characteristics of optical fiber waveguides are reviewed. Included in the review are techniques for measuring attenuation, delay distortion, refractive-index profile, fiber diameter, and mechanical strength. Since establishment of accurate measurement procedures cannot be accomplished without some knowledge of the physical mechanisms controlling the parameters to be measured, a brief review of the dominant causes of attenuation and modal delay in fibers is also included.

*****

1.2 Multiple Parameters

F. Bigi and G. Bonaventura

CCITT studies on optical fibres cables measurements

Tech. Digest, Symp. Optical Fiber Meas.-1980, 129-135; 1980, U.S. Govt. Printing Office

*****

J. F. Clarke and I. Mackenzie

A microprocessor based system for characterisation of optical fibres

Digest, Mess. in der opt. Nachrichten., Berlin, 47-52; 1980, VDE-Verlag

*****

L. G. Cohen and S-J. Jang

An interrelationship between loss and dispersion in multimode fibers

Tech. Digest, Symp. Optical Fiber Meas.-1980, 55-58; 1980, U.S. Govt. Printing Office.

*****

Leonard G. Cohen, Peter Kaiser, and Chinlon Lin

Experimental techniques for evaluation of fiber transmission loss and dispersion

Proc. IEEE 68:1203-1213; 1980

This paper describes state-of-the-art measurement techniques for the characterization of fiber loss and dispersion. Special emphasis is placed on the achievement of high measurement accuracy, and on novel techniques to determine the loss and dispersion of single-mode and graded-index fibers in the 0.8 to 1.7-μm wavelength region where fiber loss and material dispersion are both small.

*****

W. E. Freyhardt

Betriebsmessverfahren fur Lichtwellenleiter und optische Kabelstrecken (Working measurement procedures for optical waveguide and optical cable links)

Digest, Mess. in der opt. Nachrichten., Berlin, 53-61; 1980, VDE-Verlag

*****

M. Hof

Das "Optical Time Domain Reflectometer" zur Messung von Dampfung, Modemixing, Kopplungsverlusten, etc., an Fiberoptik-Kabeln (The optical time domain reflectometer for measuring attenuation, modemixing, coupling losses, etc., in fiberoptic cable)

Digest, Mess. in der opt. Nachrichten., Berlin, 41-45; 1980, VDE-Verlag

*****

G. Thomas Holmes

Propagation parameter measurements of optical waveguides

SPIE 224:138-143; 1980

Improvements in optical waveguide manufacturing processes have reduced the attenuation rate to approximately the material limit imposed by Rayleigh scattering. Today there is a need to develop measurement techniques or procedures which can be used to predict the overall system insertion loss and bandwidth. Multimode propagation in graded waveguides makes it difficult to define the attenuation rate and bandwidth without referencing the particular source power distribution used in making the measurement. This paper will discuss the problems in making these measurements and will present a recent model and results which can be used to predict system performance.

*****

M. Kaiser

Universelle Messanordnung fur Faser-Lichtleiter (Universal measurement arrangement for fiber lightguide)

Digest, Mess. in der opt. Nachrichten., Berlin, 90-95; 1980, VDE-Verlag

*****

F. P. Kapron, F. M. E. Sladen, P. M. Garel-Jones, D. G. Kneller

Attenuation and pulse broadening along concatenated fiber links

Tech. Digest, Symp. Optical Fiber Meas.-1980, 63-66; 1980, U.S. Govt. Printing Office

*****

R. Th. Kersten and T. Le-Hiep

Messung von Faserreigenschaften im Wellenlangenbereich 0.85 bis 1.7 μm (Measurements of fiber characteristics in the wavelength range from 0.85 to 1.7 μm)

Digest, Mess. in der opt. Nachrichten., Berlin, 66-71; 1980, VDE-Verlag

*****

F. Krahn and D. Rittich

Messtechnik fur optische Nachrichtentechnik bei hoheren Wellenlangen (Measurement techniques for optical telecommunications at longer wavelengths)

Digest, Mess. in der opt. Nachrichten., Berlin, 45-46; 1980, VDE-Verlag

*****

R. E. Love

Waveguide fiber standards

Tech. Digest, Symp. Optical Fiber Meas.-1980, 135-143; 1980, U.S. Govt. Printing Office

*****

E. F. Murphy, R. W. Lapierre, C. F. Laing

Industrialized system for the automated measurements of the optical properties of waveguide fibers

Tech. Digest, Symp. Optical Fiber Meas.-1980, 105-111; 1980, U.S. Govt. Printing Office

*****

F. Scudieri

Differential interferometric method for optical fiber testing

Appl. Opt. 19:404-408; 1980

A new differential interferometric method of determining the optical characteristics of cylindrical systems is presented. In particular it is applied to the study of a step-index optical fiber where small changes in geometric and optical characteristics have been introduced.

*****

M. P. Smid

The preparation of standards for "optical fibers and cables" within the International Electrotechnical Commission

Tech. Digest, Symp. Optical Fiber Meas.-1980, 121-127; 1980, U.S. Govt. Printing Office

*****

Bruno Costa

Comparison between various fibre characterization techniques

Proc. (Supp.), Opt. Commun. Conf., Amsterdam, II-1--II-5; 1979

*****

B. L. Danielson, G. W. Day, and D. L. Franzen

Propagation measurements in multimode optical waveguides

Proc., Fiber Opt. Comm.-78, 205-207; 1979, Information Gatekeepers

This talk provides an overview of the difficulties associated with adequate propagation measurements. Work at NBS and other laboratories is reviewed.

*****

G. W. Day

Fiber measurements: Quality and cost

Proc., Int. Conf. Commun. Boston, 10.4.1-10.4.3; 1979, IEEE

Several points which should be considered by groups writing standard measurement procedures for optical fiber waveguides are discussed. These include the quality of measurements, the factors limiting that quality, the prospect for improvement, and the cost of measurements. Some of the points are illustrated with data from measurement comparisons.

*****

M. Eriksrud, A. Hordvik, N. Ryen, and G. Nakken

Comparison between measured and predicted transmission characteristics of 12 km spliced graded-index fibers

Opt. Quantum Electron. 11:517-523; 1979

Cumulative attenuation and dispersion were measured along a 11.7 km fibre link consisting of 10 spliced fibres and compared to measurements on the individual fibres. Four different procedures were used for the loss measurements, and the effect of transient losses in the link provided transient losses due to high-order modes were eliminated in the individual measurements. Pulse dispersion measurements were made without the use of any mode scrambler. The cumulative dispersion measurements clearly showed a significant correlation between non-adjoining fibres, and the observed pulse width exhibited more of a linear than a square root dependence on length.

*****

Ikutaro Kobayashi, Kenji Okada, and Masamitsu Tokuda

Measuring equipment for optical fiber transmission systems

Rev. Elect. Commun. Lab. (Japan) 27:1029-1048; 1979

Measuring equipments have been designed for use on a field trial of optical fiber transmission systems. Examination results have been good through their full use in the field trial.

These developed measuring equipments consist of about fifteen kinds of sets and formulate a hierarchical measuring system for optical transmission systems.

However, many problems remain to be solved in order to obtain more accurate results. Many of the problems are closely concerned with the performance or unstableness of optical device used. Many efforts have been focussed on improving characteristics or searching for measuring methods immune from unstableness.

*****

F. Krahn, W. Meininghaus, and D. Rittich

Measuring and test equipment for optical cable

Philips Telecomm. Rev. 37:241-249; 1979

This article gives an overview of the instrumentation used in fibre optic communications. It goes into the properties of equipment required for the field measurement of optical attenuation and dispersion, and for fault location.

*****

I. Nouchi, A. Jacques, and L. D'Auria

Characteristics against length of silicone-clad silica optical fibres

Electron. Lett. 15:315-316; 1979

The letter is concerned with length dependence of the transmission characteristics of a low-loss silicone-clad silica fibre (up to 5 km). It is observed that a quasi-steady-state condition (fibre characteristics independent of launching conditions) is obtained at 100 m long before true equilibrium (bandwidth proportional to $L^{-1/2}$) attained at 2.5 km.

*****

Robert W. Ramirez

Evaluating fibers digitally

Laser Focus 15:46-52; April 1979

*****

Masamitsu Tokuda, Tadatoshi Tanifuji, Mitsuhiro Tateda, and Ikutaro Kobayasi

Far-end measuring methods for transmission characteristics of graded index fiber

Conf. Rec., Int. Conf. Commun., Boston, 36.2.1-36.2.6; 1979, IEEE

The optical loss measuring system composed of stable light source (LED), dummy fiber and accurate optical power meters has been developed. Measuring conditions, such as dummy fiber length and cut fiber length used to measure the input power into measured fiber, were studied to estimate optical loss of long spliced fibers from those of each constituent fiber.

A novel far-end automatic measuring system of baseband frequency response based on frequency-domain techniques has been proposed. Measured fiber (graded index fiber) is excited by step index multimode fiber. It has been found that the method is excellent in regard to baseband frequency response reproducibility. Simple and useful formula has been proposed to estimate baseband bandwidth of spliced long optical fibers from that of each constituent fibers.

It has been determined that transmission characteristics could be measured using far-end measuring methods by making use of these methods during the field trial.

*****

M. Eve, P. C. Hensel, D. J. Malyon, B. P. Nelson, J. R. Stern, J. V. Wright, and J. E. Midwinter

Transmission studies on three graded-index fibre cable links installed in operational ducts

Opt. Quantum Electron. 10:253-265; 1978

This paper reports the transmission measurements made on 40 km of graded-index fibre which have been cabled and installed in operational ducts for use in 8 and 140 Mbit s^{-1} systems. Extensive loss and bandwidth measurements were made at all stages of the programme, both before and after cabling and also in the field using two mobile test vehicles. The problems of obtaining meaningful and reproducible measurements are discussed and the stability of the measurements between the various cabling and installation stages is assessed. The results have been analysed in conjunction with additional laboratory measurements and a number of important propagation effects have been brought to light.

*****

M. Eve, P. C. Hensel, D. J. Malyon, B. P. Nelson, and J. V. Wright

Techniques for measuring the transmission properties of optical-fibre cables

Post Off. Elect. Eng. J. (GB) 71:122-129; 1978

This article describes the techniques used by the British Post Office to measure the transmission properties of optical-fibre cables, both in the laboratory and in the field. The measurements include the determination of loss, bandwidth and refractive-index profile. Fault location by the observation and measurement of backscattered light in the fibre is also described.

*****

Hienz Friedberg and Werner A. Kral

Grasfaserkabel and Messverfahren (Glass fiber cable and measurement methods)

Nachrichten Elektronik 32:85-88; 1978

*****

Ikutaro Kobayashi, Yohji Jujii, Nobuo Suzuki, Kohichi Aoyama, and Masaki Koyama

Measuring equipment for an experimental optical fiber transmission system

Rev. Elect. Commun. Lab. (Japan) 26:712-726; 1978

Measuring equipment have been trial developed for use on an experimental optical fiber transmission system. Efforts have been focused on the following items:
(1) Standardizing measuring methods.
(2) Realizing handy measuring equipment for practical use.
(3) Clarifying inherent problems in measuring fiber transmission characteristics etc.
The developed measuring equipment were fully used for testing laid fiber cables.

Five fiber measuring equipment have been manufactured for trial.
(1) Fiber transmission equipment.
(2) Splice and connector monitoring meter.
(3) Spectral loss measurment set.
(4) Material dispersion measurement set.
(5) Optical power meter.
Many measuring methods are applicable to one measuring set. Their methods have been compared with each other and one has been chosen in order to minimize measuring errors.

Manufactured equipment would become prototypes of measuring equipment for practical use in future applications. Through manufacturing these prototypes, practical or inherent problems involved in optical fiber measuring equipment become clear.

*****

Ikutaro Kobayashi and Masaki Koyama

Step-index multimode fiber transmission characteristics

Rev. Elect. Commun. Labs. (Japan) 26:500-508; 1978

This paper reports results of investigating various step-index fiber characteristics and formulas resulting from measurements and theoretical study. In particular, emphasis is put on the following items:
(1) Determining fundamental optical fiber characteristics for communication channel use.
(2) Accumulating measured data on fiber transfer functions and other transmission characteristics.
(3) Determining fundamental fiber parameters.
(4) Finding feasible optical fiber application fields.
(5) Clarifying inherent optical fiber problems.

Various measured characteristics and their formulas are shown. They are very important in designing fiber transmission systems as well as understanding fundamental fiber characteristics. Through the fiber investigation, it has also proved important to treat fiber transmission characteristics in the frequency domain.

*****

R. E. Love and D. B. Keck

Characteristics of optical fiber waveguides

Opt. Eng. 17:114-119; 1978

The design and performance of optical cables, connector hardware and communciation systems are governed by the light transmission and coupling characteristics of waveguide fibers. These characteristics depend upon waveguide design and materials as well as manufacturing tolerances. Measurement methods and limitations are discussed, and use and interpretation of waveguide specifications in designing optical links and predicting overall performance are shown.

*****

K. Mikoshiba and H. Kajioka

Transmission characteristics of multimode W-type optical fiber: Experimental study of the effect of the intermediate layer

Appl. Opt. 17:2836-2841; 1978

The transmission mechanism of a multimode W-type optical fiber is clarified by the experimental study of the effect of the intermediate layer on the transmission characteristics. It is shown that control of the layer width is an effective means for achieving the desired loss and bandwidth. A W-type fiber with a thick intermediate layer has a transmission loss on the order of 2 dB/km. To determine the transmission characteristics of a W-type fiber applicable to system design, the length dependence of several fiber characteristics is investigated. Concepts such as splices used as mode scramblers and the effect of the intermediate layer as a barrier against OH absorption loss are introduced. The wavelength dependence of microbending loss of a W-type fiber is also described.

*****

William M. Simpson, G. Thomas Holmes, Walter F. Love and Miles E. Vance

Semi-automated measurements of the transmission medium

SPIE 150:133-150; 1978

The measurement sequence for the characterization of graded-refractive-index optical waveguide fibers in a manufacturing environment is presented. The sequence has been designed for minimum human interaction and high throughput. The optical fibers, characterized by attenuation rate, bandwidth, numerical aperture, and optical core diameter, are measured on a quality assurance system driven by a minicomputer. This semi-automated sysem, consisting of optical and electronic hardware and software for complete characterization, is described. Finally, the measurement methods and current test conditions are presented.

*****

P. W. Black, A. Cook, A. R. Gilbert, M. M. Ramsay, and J. R. Stern

The manufacture, testing and installation of rugged fibre-optic cables

Proc., Third Eur. Conf. Opt. Commun., Munich, 50-52; 1977

*****

S. Kawakami

New principles to measure loss and mode-conversion parameters of multimode fibres

Elect. Lett. 13:706-707; 1977

We derive an equation that relates the differences between the mean transit times of modes of a multimode fibre with loss, multimode dispersion and mode-conversion parameters. The concept of dynamic equilibrium is developed for the temporal difference. Further, we propose a new method of simultaneous measurement of loss and mode-conversion parameters which utilises the temporal difference.

*****

E. A. J. Marcatili

Factors affecting practical attenuation and dispersion measurements

Tech. Digest, Opt. Fiber Trans. II, Williamsburg, TuE1-1--TuE1-4; 1977, Opt. Soc. Am.

*****

T. Matsumoto and I. Kobayashi

Transmission characteristics of a graded-index multimode fiber

Tech. Digest, IOOC-77, Tokyo: 439-441; 1977

A graded-index multimode fiber is a promising transmission line of communication systems because of its wide bandwidth. Its characteristics, however, are said to be critical and depend on some conditions. In this paper, the characteristic dependence of a graded-index multimode fiber on wavelength and excitation conditions is studied experimentally.

*****

Tomoyuki Otsuka, Eizo Miyauchi, and Toshiaki Ogino

Automated measurement system for optical fibers

Fujitsu Sci. Tech. J. (Japan) 13:69-90; 1977

This paper reports on an automated measurement system which allows rapid and reliable characterization of optical fibers.

The system consists of five optical measuring setups for loss spectrum, far-field, near-field, impulse response and baseband frequency response. The system adopts a minicomputer PANAFACOM U-300 with an interface for data acquisition and data processing controlled by FORTRAN based programs.

The average measurement time has been reduced at least to one-tenth compared with that by conventional manual methods. The repeatedly measured results indicate that loss spectrum can be measured with an accuracy of ±0.02--0.15 dB, core and cladding diameters of ±1%, refractive index profile constant of ±3%, numerical aperture of ±1%, pulse width and bandwidth of ±14% in terms of standard deviation.

*****

M. Chown and R. Worthington

Measurement of transmission properties of optical fibers

Elect. Commun. 51:242-248; 1976

Now that attenuation in optical fibers has been reduced to a commercially viable level, the early preoccupation with this parameter is giving way to a study of the more complex parameters concerned with transmission quality.

*****

L. Jeunhomme, A. Cozannet, R. Bouillie, and J. P. Hazan

Mesure des caracteristiques de transmission de conducteurs optique (Measurements of the transmission characteristics of optical conductors)

L'Onde Electron. 56:564-571; 1976

The measurement methods used and the main results obtained in three French laboratories (Laboratoires de Marcoussis, CNET Lannion, LEP) are presented here. The measurements of interest here concern mainly the users of optical conductors in transmission systems and therefore, the interest is focused onto the transmission characteristics. The influence of the measurement conditions on the obtained result is shown for some specific characteristics and we deduce conclusions for a better definition and a normalisation of measurement methods. Especially, measurements performed with the steady-state launching conditions are seen to be necessary, in order to obtain significant results.

*****

L. Jeunhomme, A. Cozannet, R. Bouillie, and J. P. Hazan

Measurement methods of optical conductors transmission characteristics

Digest, Second Eur. Conf. Opt. Fibre Commun., Paris, 123-134; 1976

The measurement methods used and the main results obtained in three french laboratories (Laboratoires de Marcoussis, CNET Lannion, LEP) are presented here. The measurements of interest here concern mainly the users of optical conductors in transmission systems and therefore, the interest is focused onto the transmission characteristics. The influence of the measurement conditions on the obtained results is shown for some specific characteristics and we deduce conclusions for a better definition and a normalisation of measurement methods. Especially, measurements performed with the steady-state launching conditions are seen to be necessary, in order to obtain significant results.

*****

J. E. Midwinter

Trends in optical fibre transmission research

Nature 261:371-376; 1976

Recent advances in the manufacturing technology of low loss optical fibers have made possible serious systems design and testing. But this has highlighted the fact that the mechanisms involved in the propagation of light in multimode fibres were at best, poorly understood. New measurement techniques are now being used to check more sophisticated theoretical analyses of propagation in "imperfect" and cabled fibres and are leading to a deeper understanding of this new transmission medium, its possibilities and its limitations.

*****

L. G. Cohen, P. Kaiser, J. B. MacChesney, P. B. O'Connon, and H. M. Presby

Transmission properties of a low-loss near-parabolic-index fiber

Appl. Phys. Lett. 26:472-474; 1975

Pulse dispersion, refractive-index profile, and loss measurements were made on a low-loss graded-index optical fiber fabricated by a chemical vapor deposition technique. The transmission loss spectra had a minimum value of 3.8 dB/km at 1.06-μm wavelength. The core refractive index had a power-law profile with an exponential coefficient of 2.2±0.1. Mode-mixing effects and the near-parabolic-index profile in a 5.6-km extrapolated fiber length (actual length = 1.12 km) reduced modal dispersion by a factor of 17 from the result expected for an ungraded step-index fiber.

*****

W. J. Stewart

Fibre characterization by use of the relation between the characteristics of leaky modes in optical fibres and the fibre parameters

Proc., First Eur. Conf. Opt. Fibre Comm., London, 21-23; 1975, IEE

*****

A. H. Cherin, L. G. Cohen, W. S. Holden, C. A. Burrus, and P. Kaiser

Transmission characteristics of three Corning multimode optical fibers

Appl. Opt. 13:2359-2354; 1974

The loss spectra, refractive-index profiles, numerical apertures, and pulse dispersion characteristics of three multimode optical fibers made by Corning Glass Works have been measured at Bell Laboratories. The lowest transmission loss, 4.3-6.8 dB/km, was observed at 1.06-μm wavelength; in the 0.8-0.9-μm spectral region the losses ranged from 6.6 dB/km to 11.6 dB/km. The numerical apertures of the fibers, designated as Nos. 1, 2, and 3, were calculated from the measured refractive-index differences to be 0.133, 0.157, and 0.121, respectively. Pulse dispersion due to multimode effects in fiber No. 1 (1 km long) was 8.4 nsec at 0.9-μm wavelength; the valuess were 6.0 nsec for fiber

No. 2 (0.363 km long) and 2.6 nsec for fiber No. 3 (0.290 km).

*****

Donald B. Keck

Spatial and temporal power transfer measurements on a low-loss optical waveguide

Appl. Opt. 13:1882-1888; 1974

Experimental measurements of the spatial and temporal transfer of power of a 225-m length of low-loss optical waveguide have been made. In particular, measurement of the angular attenuation showed substantial loss of the high order modes, which reflected itself in an ~8.2 nsec/km decrease in measured dispersion. Additionally there was a reduction of the effective numerical aperture from 0.15 to 0.12. Negligible mode coupling was observed in this particular waveguide, which allowed a phenomenological calculation of temporal output for an assumed uniform excitation of all modes. This agreed well with experimental measurements. Calculation of this output from knowledge of the index profile is presently not in agreement, and some possible reasons are indicated.

*****

D. Gloge and E. A. J. Marcatili

Multimode theory of graded-core fibers

Bell Sys. Tech. J. 52:1563-1578; 1978

New technologies of fiber manufacture and a demand for unusual fiber qualities in communication systems have intensified the interest in a comprehensive theory of multimode fibers with nonuniform index distributions. This paper deals with a general class of circular symmetric profiles which comprise the parabolic distribution and the abrupt core-cladding index step as special cases. We obtain general results of useful simplicity for the impulse response, the mode volume, and the near- and far-field power distributions. We suggest a modified parabolic distribution for best equalization of mode delay differences. The effective width of the resulting impulse is more than four times smaller than that produced by the parabolic profile. Of course, practical manufacturing tolerances are likely to influence this distribution. A relation is derived between the maximum index error and the impulse response.

2. ATTENUATION MEASUREMENTS

2.1 General

J. P. Dakin and W. A. Gambling

Theory of scattering from the core of a multimode fibre waveguide

Opt. Commun. 10:195-199; 1974

A theory suitable for the interpretation of measurements of light scattering from cladded multimode optical fibres is presented. The model used is based on geometrical optics and enables the effects of depolarization, the angular distribution of the propagating beam, as well as refraction and reflection at the core cladding interface to be taken into account. Good agreement is obtained between the theory and experiment.

*****

G. W. Day and G. E. Chamberlain

Results of a recent attenuation measurement comparison among U.S. optical waveguide manufacturers

Proc. (Supp.), Opt. Commun. Conf., Amsterdam, 19.4-1--19.4-4; 1979

*****

A. Diekema, L. H. M. Engel, G. A. M. Goltstein, P. Matthijsse, and J. W. Versluis

Comparative measurements regarding the attenuation of optical fibres for the Eindhoven-Helmond field trial

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 27-30; 1980, U.S. Govt. Printing Office

*****

R. M. Hawk

Multimode waveguide attenuation measurements

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 1-9; 1980, U.S. Govt. Printing Office

*****

W. Heitmann, C. R. Day, and U. Zwick

Breitbandige spektral Dampfungsmessungen an Lichtwellenleitern--ein Messvergleich der Gruppe COST 208 (Broadband specral attenuation measurements on optical waveguide--a measurement comparison of Group COST 208)

Digest, Mess. in der Opt. Nachtrichten., Berlin, 116-120; 1980, VDE-Verlag

*****

M. Kaiser and U. Zwick

Vergleich verschiedener Messverfahren fur die Faserdampfung (Comparison of different measurement procedures for fiber attenuation)

Digest, Mess. in der opt. Nachrichten., Berlin, 139-141; 1980, VDE-Verlag

*****

Jun-ichi Sakai

Microbending loss evaluation in arbitrary-index single-mode optical fibers. Part 1: Formulation and general properties

IEEE J. Quantum Electron. QE-16:36-44; 1980

Microbending loss formula is derived for arbitrary-index profile optical fibers by using analytical curved fiber fields to the first-order perturbation theory. Relation between loss and fiber curvature power spectral statistics is studied in detail. Normalized frequency giving the minimum microbending loss value scarcely depends on the power spectrum. The larger the propagation constant differnece between the guided and quasi-guided modes, the smaller the microbending loss is in regard to wavelength, relative index difference, and normalized frequency dependence. The obtained formulas for single-mode fiber show the same dependence as the graded-index multimode fiber, with respect to fiber structure and curvature statistical parameters.

*****

Jun-ichi Sakai

Microbending loss evalution in arbitrary-index single-mode optical fibers. Part II: Effects of core index profiles

IEEE J. Quantum Electron. QE-16:44-49; 1980

Microbending losses in single-mode fibers with several types of core refractive index profiles are compared. Numerical calculations were carried out to characterize fibers with step, power-law, W and ring-shaped index profiles. Step-index and W fibers exhibit a small excess loss near the single-mode operation upper limit. However, permissible offset misalignment in fiber splice at constant microbending loss is nearly identical for step, power-law, and W fibers. An index dip at the core center has an undesirable influence on the required splicing accuracy. The effects of fiber curvature statistics and index profile parameters are investigated in detail.

*****

G. Cancellieri

Misure di attenuazione nell fibre ottiche (Measurement of attenuation in optical fibres)

Alta Freq. 47:151-154; 1978

*****

M. H. Reeve, M. C. Brierly, J. E. Midwinter, K. I. White

Studies of radiative losses from multimode optical fibres

Opt. Quantum Electron. 8:39-42; 1976

We describe measurements in which the radiative losses from a multimode fibre have been resolved into three components. These are the Rayleigh Scatter component from the material, the loss by tunnelling from the modes closest to cut-off into the surrounding material, and the forward scatter loss caused by imperfections in the fibre that are large compared to a wavelength.

2.2 Direct Methods

R. Bondiek

Prazisionsmessender fur optische Messungen (Precision source for optical measurements)

Digest, Mess in der opt. Nachrichten., Berlin, 84-89; 1980, VDE-Verlag

*****

A. H. Cherin

A fiber concatenation experiment using a standardized loss measurement method

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 19-22; 1980, U.S. Govt. Printing Office

*****

A. H. Cherin and W. B. Gardner

Measurement standards for multimode telecommunication fibers

SPIE 224:144-148; 1980

The emergence of optical fibers as an important communications medium has created the need for standardized test procedures for evaluating fiber transmission characteristics.

In this paper we will review some of the standardization efforts aimed at improving the agreement between optical fiber measurements made at different location. We will alos outline the characteristics that a standardized test procedure should have to be useful to the fiber optics industry. In addition, the procedures followed in an industry wide round robin measurement study will be described to illustrate the current status of standardized fiber optic loss measurements.

*****

Allen H. Cherin and William B. Gardner

Fiber measurement standards

Laser Focus 16:60-65; August 1980

*****

R. M. Hawk

Multimode waveguide attenuation measurements

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 1-9; 1980, U.S. Govt. Printing Office

*****

W. Heitmann, C. R. Day, and U. Zwick

Broadband spectral attenuation measurements on optical fibres--an interlaboratory comparison by members of Cost 208

Digest, Sixth Eur. Conf. Opt. Commun., York, 148-151; 1980, IEE

*****

G. T. Holmes

Launch dependent attenuation measurements on a 10-kilometer concatenation experiment

Digest, Sixth Eur. Conf. Opt. Commun., York, 144-147; 1980, IEE

*****

L. C. Hotchkiss

Automated loss measurement set for optical cables

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 23-26; 1980, U.S. Govt. Printing Office

*****

P. Kaiser

Loss measurements of graded-index fibers: Accuracy versus convenience

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 11-14; 1980, U.S. Govt. Printing Office

*****

K. Kimmich and U. Zwick

Automatisierter Messplatz fur spektrale Dampfungsmessung optischer Fasern bis 1800 nm (Automatic measurement facility for spectral attenuation measurement of optical fibers to 1800 nm)

Digest, Mess. in der opt. Nachrichten., Berlin, 62-65; 1980, VDE-Verlag

*****

A. B. Sharma, E. J. R. Hubach, S. J. Halme

An accurate method for the measurement of fiber attenuations

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 15-18; 1980, U.S. Govt. Printing Office

*****

F. T. Stone and P. H. Krawarik

Mode elimination in fiber loss measurements

Appl. Opt. 18:756-758; 1979

*****

Mitsuhiro Tateda, Tsuneo Horiguchi, Masamitsu Tokuda, and Naoya Uchida

Optical loss measurement in graded-index fiber using a dummy fiber

Appl. Opt. 18:3272-3275; 1979

The utility of an auxialiary fiber, called a dummy fiber, is investigated for optical fiber loss measurements. The dummy fiber is spliced and used to excite the test fiber. Excess loss caused by undesirable modes is found to be reduced to less than 0.05 dB by using a 500-m dummy fiber and choosing the test fiber cut length to be 2 m for reference. Loss linearity to the fiber length is examined on 6 km-spliced fibers, and satisfactory agreement is obtained between the total loss and the sum of the individual fiber and splice losses.

*****

P. H. Wendland and D. N. Horwitz

A decibel measuring instrument for fiber optics

Proc., Fiber Opt. Commun.-79, Chicago, 121-124; 1979

Decibel power units are widely utilized to characterize the output of sources, the loss of cables and connectors/splices, and the response of photoreceivers. This paper describes the operation and design of a portable instrument which makes these measurements in both absolute dBm units and relative dB units over a 900 dB range.

*****

Ettore Bianciardi, Giovanni Cancellieri, and Maurizio Zoboli

Non-destructive spectral loss measurements in coated and jacketed fibres

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 183-188; 1978

A non destructive spectral attenuation measurement for uncoated fibres has been extended also to coated and jacketed ones. This measurement technique has also been performed using different kinds of Light Emitting Diodes as optical sources. This method is proposed as complementary with respect to the backscattering technique.

*****

P. Kaiser

NA-dependent spectral loss measurements of optical fibers

Trans. IECE Japan E61:225-229; 1978

Steady-state losses of optical fibers have been obtained by launching beams of different numerical apertures and by measuring the losses and the corresponding radiation patterns at both ends of the fiber. The steady-state losses are associated with that radiation pattern whose distribution remains essentially unchanged. Other information obtainable from NA-dependent loss measurements include, for example, the excess scattering losses in graded-index fibers due to the increased concentration fluctuations near the fiber axis, and the influence of a central index dip on fiber losses. The NA-dependent spectral-loss characteristics of a plastic-clad silica fiber, and of 0.22 and 0.34 NA Ge-B-doped fibers are presented as examples.

*****

Robert Olshansky and Susan M. Oaks

Differential mode attenuation measurements in graded-index fibers

Appl. Opt. 17:1830-1835; 1978

An automated apparatus is described for measuring mode-dependent scattering and total attenuation in graded-index waveguides. Measurements are reported for two low-loss waveguides and several high-loss waveguides. The results illustrate the ability of this technique to identify different types of loss mechanisms.

*****

L. Wilson and M. J. Buckler

Automated spectral loss measurement of optical fibres

Opt. Laser Tech. 10:197-199; 1978

An automated system that precisely measures the spectral loss of optical fibres at wavelengths from 0.63 μ to 1.51 μ has been developed. A description of the system, along with measurement techniques used and typical results are given in this paper.

*****

M. Eve

Novel technique for the measurement of differential mode attenuation in graded-index fibres

Electron. Lett. 13:744-745; 1977

A novel technique for the determination of differential mode attenuation in a graded-index fibre is presented. Its originality lies in its experimental simplicity and small data processing involved.

*****

P. Kaiser

Numerical-aperture-dependent spectral-loss measurements of optical fibers

Tech. Digest, IOOC-77, Tokyo, 267-270; 1977

Numerical-aperture-dependent loss measurements are not only required for accurately determining the steady-state losses, but they are also a powerful tool to probe the detailed loss characteristic of an optical fiber. The losses of silicone-clad and Ge-doped silica fibers are discussed as examples.

*****

B. N. Klyushinik, A. I. Maltabar, N. I. Voloshina, and V. N. Petrova

Measurement of attenuation indices for polymer lightguides

Opt. Spectrosc. (USSR) 43:662-664; 1977

The form of the light transmission of polymer light-guides is investigated as a function of their length. The layout of the measuring device and typical results are given. A procedure for processing the results by the method of least squares in order to find the attenuation coefficients is presented and proved. Student's distribution is used to find confidence intervals for the attenuation coefficients. Typical values of the resulting discrepancies are less than 2%. A simple exponential dependence between the light flux and the length of the fibers is established in the region of lengths investigated.

*****

T. Naruse, Y. Sugawara, M. Tanaka, Y. Hattori, K. Yoshimura, T. Yamanishi, and N. Uchida

Fiber parameter dependence of excess loss for step-index fibers

Tech. Digest, IOOC-77, Tokyo, 271-274; 1977

Experimental investigations have been made for step-index fibers to clarify effects of core and outer diameters of fiber, refractive index difference, and jacket diameter on loss increase due to bending and microbending. On the basis of the results, low loss fiber cables stable to temperature change have been fabricated by carefully controling manufacturing processes.

*****

R. Olshansky

Differential mode attenuation in graded-index optical waveguides

Tech. Digest, IOOC-77, Tokyo, 423-426; 1977

The causes of differential mode attenuation and its effect on optical measurements are discussed. An automated measurement is described for determining the mode-dependence of both the total and scattering losses of optical waveguides. Results will be reported which illustrate the ability of this technique to identify the sources of attenuation from analysis of its mode-dependence.

*****

R. Olshansky and D. A. Nolan

Mode dependent attenuation in parabolic optical fibers

Appl. Opt. 16:1639-1641; 1977

A previous study of excess attenuation caused by slowly varying perturbations is extended to optical fibers with parabolic index profiles. For random diameter variations, total losses are found to be essentially the same in step and parabolic fibers.

*****

R. Olshansky, S. M. Oaks, and D. B. Keck

Measurement of differential mode attenuation in graded-index fiber optical waveguides

Tech. Digest, Opt. Fiber Trans. II, Williamsburg, TuE5-1--TuE5-4; 1977, Opt. Soc. Am.

*****

T. Yamada, H. Hasimoto, K. Inada and S. Tanaka

Launching dependence of transmission losses of graded index optical fiber

Tech. Digest IOOC-77, Tokyo, 263-266; 1977

This paper reports the launching dependence of transmission losses of a graded index optical fiber in comparison with a step index optical fiber. The launching dependence of a graded index fiber was much smaller than that of a step index fiber when the fibers are free from random bends.

*****

M. Eve, A. M. Hill, D. J. Maylon, J. E. Midwinter, B. P. Nelson, J. R. Stern, and J. V. Wright

Launching independent measurements of multimode fibres

Digest, Second Eur. Conf. Opt. Fibre Commun., Paris, 143-146; 1976

The problems of launching dependence are discussed with a view to obtaining reproducible measurements of loss and bandwidth on low loss multimode fibres. The use of a mode scrambling technique is suggested as a means of standardizing the input mode distribution in order to overcome these problems. The effectiveness of the technique has been demonstrated by measuring the bandwidth of a step-index fibre using three different measurement systems employing different sources.

The possibility is also examined of producing a standardized distribution which matches the stable mode distribution of a fibre so that relevant loss measurements may be made on lengths of fibre which subsequently form part of a multikilometre route.

*****

I. S. Goldfarb and T. M. Lozovskaya

A method of measuring the light transmission of glass-fiber without disturbing the integrity of the objects being tested

Sov. J. Opt. Technol. 43:738-740; 1976

The equipment is shown schematically, its operation described, and its mode of operation analysed. Results are compared with standard methods and good agreement is found. Application to measurement of transmission of optical cables already laid in place is briefly discussed.

*****

R. Olshansky, M. G. Blakenkamp, and D. B Keck

Length-dependent attenuation measurements in graded-index fibers

Digest, Second Eur. Conf. Opt. Fibre Commun., Paris, 111-113; 1976

A launch condition commonly used in attenuation measurements establishes very different modal power distributions in step and parabolic fibers. By uniformly illuminating the fiber core with a launch beam having a limited numerical aperture, one can avoid exciting the high-order guided modes and leaky modes of a step fiber. This is not true for parabolic fibers, which are thus predicted to show a length-dependent attenuation when measured by this method. Length-dependent attenuation measurements of several four-kilometer long parabolic fibers are reported. The attenuation measured by a standard method is found to yield a value which is 1.2 dB/km higher than the steady-state attenuation.

*****

R. Olshansky and D. A. Nolan

Mode-dependent attenuation of optical fibers: Excess loss

Appl. Opt. 15:1045-1047; 1976

A theory is presented for calculating the excess loss produced by random perturbations of optical fibers. The theory is applicable to perturbations whose longitudinal spatial frequencies are below the range required for mode coupling. To illustrate the method, losses due to diameter variations are calculated for the case of a step-index optical fiber. The diameter variations are found to produce a strong attenuation of the higher order modes. The total excess loss is approximately wavelength independent.

*****

P. Kaiser and H. W. Astle

Measurement of spectral total and scattering losses in unclad optical fibers

J. Opt. Soc. Am. 64:469-474; 1974

Spectral losses in unclad optical fibers have been measured in the region between 0.5 and 1.12 μm with the filtered light of a xenon-arc lamp. Total losses were obtained nondestructively by measuring the light refracted from the fiber when it was immersed in a higher-index liquid. The radial irradiance distribution of the refracted light was used as a measure of the mode spectrum. Because scattering losses could be shown to approach the Rayleigh-scattering limit, and total losses were between 6 and 8 dB/km, i.e., 75 to 85% per kilometer, for some of the highest-purity synthetic vitreous silicas, we tentatively conclude that the spectral losses of unclad fibers represent a good approximation to the spectral losses of the bulk material.

*****

D. B. Keck and A. R. Tynes

Spectral response of low-loss optical waveguides

Appl. Opt. 11:1502-1506; 1972

The attainment of 20-dB/km attenuation in experimental single-mode glass optical waveguides has spurred interest in their use for optical communications. The primary wavelength region of interest is in the red or near-infrared region of the spectrum. In this work independent attenuation measurements from 600 nm to 1060 nm have been made on low-loss waveguides and bulk cladding glass, using both laser and scanning-prism monochromator sources. Three bands were observed in the waveguides, at 725 nm, 875 nm, and 950 nm, and identified as due to OH in the glass. Absorptions too small to be precisely measured in the bulk glass are seen to be exceedingly important in the waveguides and easily measured in them.

*****

Arthur R. Tynes

Measuring loss in optical fibers

Bell Lab. Rec. 50:303-311; 1972

*****

A. R. Tynes, A. David Pearson, and D. L. Bisbee

Loss mechanisms and measurements in clad glass fibers and bulk glass

J. Opt. Soc. Am. 61:143-153; 1971

Optical-loss mechanisms and transmission losses were investigated in clad glass fibers and in the bulk glass from which they were drawn. Measurements of the total losses, absorption losses, and scattering losses in both the fibers and in the bulk materials are presented and compared. Photomicrographs of scattered light were made at 90° with 0.6328-μm laser light propagating in the fiber core. These revealed the presence of an extremely large number of discrete light-scattering centers, both in the core and in the cladding. Similar photomicrographs of the bulk materials also show the presence of discrete scattering centers. Scattering centers have also been observed by means of an electron microscope; they have been shown to be crystalline, by both electron diffraction and x-ray diffraction.

2.3 OTDR Methods (See also 5.3)

E. Brinkmeyer

Backscattering in single mode-fibres

Electron. Lett. 16:329-330; 1980

The scattering process in single-mode optical fibres is considered in terms of wave optics rather than geometrical optics, which is inadequate in this case. Surprisingly, however, the result for the backscattering signal at the input end of the fibre is nearly the same as for multimode fibres.

*****

A. J. Conduit, A. H. Hartog, and D. N. Payne

Spectral- and length-dependent losses in optical fibres investigated by a two-channel backscatter technique

Electron. Lett. 16:77-78; 1980

Spectral-and length-dependent losses in optical fibres have been investigated using a two-channel technique for backscatter-waveform analysis. Results are compared with measurements obtained by the "cutback" method over the wavelength range 0.82-1.07 μm. Attenuation measurements at 0.95 μm show a significant variation in OH^- concentration along the fibre.

*****

A. J. Conduit, J. L. Hullett, A. H. Hartog, and D. N. Payne

An optimized technique for backscatter attenuation measurements in optical fibres

Opt. Quantum Electron. 12:169-178; 1980

A technique which gives maximum range and sensitivity for estimating fibre attenuation from the backscattered light has been evolved. With this technique stability problems in the source and receiver are overcome by taking two different time samples for each pulse launched into the fibre, the attenuation being derived from the ratio of the two samples. An analysis indicates that an optimum operating strategy exists in terms of the choice of system parameters such that the range over which attenuation can be measured is maximized. Results indicate that local loss measurements can be performed on fibre sections which are remote from the source by a distance corresponding to a fibre attenuation of 27 dB. Furthermore, preliminary experimental results are presented to demonstrate the viability of the technique.

*****

B. Costa, B. Sordo, U. Menaglia, L. Piccari, and G. Grasso

Attenuation measurements performed by backscattering measurements

Electron. Lett. 16:352-353; 1980

An optical fibre was circulated between various laboratories in Italy and the attenuation characteristics measured, using different experimental arrangements. The results were compared, and found in excellent agreement, demonstrating the repeatability of the technique and its suitability as a reference method for attenuation measurements.

*****

B. Costa, B. Sordo, U. Menaglia, L. Piccari, and G. Grasso

Comparison of attenuation measurements performed by the backscattering technique with different experimental set-ups

Digest, Sixth Eur. Conf. Opt. Commun., York, 160-164; 1980, IEE

*****

B. L. Danielson

An assessment of the backscatter technique as a means for estimating loss in optical waveguides

NBS Technical Note 1018, U.S. Govt. Printing Office; 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.

*****

P. Divita and U. Rossi

The backscattering technique: Its field of applicability in fibre diagnostics and attenuation measurements

Opt. Quantum Electron. 11:17-22; 1980

The evaluation of power decay along the fibre by means of the backscattering technique may be altered by the presence of unknown irregularities. In the present paper the effects of such imperfections are estimated; it is demonstrated that mainly local inhomogeneities and numerical aperture fluctuations influence backscattered power. Finally an efficient and simple method for the separation of the power decay contribution from the irregularity contribution is proposed.

*****

M. Eriksrud, S. Lauritzen, and N. Ryen

Backscatter attenuation measurements in graded index fibres

Electron. Lett. 16:877-879; 1980

A comparison is made of the attenuation values obtained by the backscattering technique and the more conventional cutback method, and the backscattering technique is shown to provide highly accurate and reliable results.

*****

P. Healey

Optical time domain reflectrometry by photon counting

Digest, Sixth Eur Conf. Opt. Commun., York, 156-159; 1980, IEE

*****

P. Healey and P. Hensel

Optical time domain reflectometry by photon counting

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 85-89; 1980, U.S. Govt. Printing Office

*****

P. Healey and P. Hensel

Optical time domain reflectometry by photon counting

Electron. Lett. 16:631-633; 1980

A photon counting technique has been used to extend greatly the range of optical time domain reflectometry or "backscatter" for fault location in optical fibre systems. A range of more than 40 dB of one-way fibre loss has been achieved even when the break was index-matched to eliminate any reflection.

*****

B. Hillerich

Optisches Sampling Reflektometer (Optical sampling reflectometer)

Digest, Mess. in der opt. Nachrichten., Berlin, 16-21; 1980, VDE-Verlag

*****

D. L. Philen

Optical time domain reflectometry on single mode fibers using a Q-switched Nd:YAG laser

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 97-100; 1980, U.S. Govt. Printing Office

*****

Luigi Piccari

Optical fibre attenuation measurements by the backscattering method: Effect of noise

Opt. Quantum Electron. 12:413-418; 1980

The backscattering method is now a well-established technique for the measurement of attenuation in multimode optical fibres. In this paper the effect of noise is evaluated in order to optimize the precision of the measurement, its dynamic range and the time required to collect the data. An experimental set-up is described and the experimental results reported.

*****

A. J. Rogers

Polarisation optical time domain reflectometry

Electron. Lett 16:489-490; 1980

A proposed new optical fibre technique will allow measurement of the spatial distribution of physical fields, and will also allow location of anomalous features in single polarisation state monomode optical fibres such as are under discussion for very high bandwidth communication.

*****

D. Schicketanz

Zukunftige Moglichkeiten des optischen Impulsreflektometers (Future possibilities of optical impulse reflectometers)

Digest, Mess. in der opt. Nachrichten., Berlin, 10-14; 1980, VDE-Verlag

*****

E. Weidel

Versweiger fur Ruckstreumessungen (Coupler for backscatter measurements)

Digest, Mess. in der opt. Nachrichten., Berlin, 187-190; 1980, VDE-Verlag

*****

P. DiVita and U. Rossi

Backscattering measurements in optical fibres: Separation of power decay from imperfection contribution

Electron. Lett. 15:467-469; 1979

A very simple and effective method is proposed for separating the actual decay of optical power from contributions due to fibre imperfection in measurements using the backscattering technique.

*****

S. M. Jensen

Observation of differential mode attenuation in graded-index fiber waveguides using OTDR

Tech Digest, Opt. Fiber Commun., Washington, 120-121; 1979, Opt. Soc. Am.

*****

Jim McNaughton

Optical time domain reflectometry in an optical cable manufacturing facility

Proc., Fiber Opt. Commun.-79, Chicago, 117-120; 1979

A simple optical Time Domain Reflectometer (optical TDR) system has been developed and this paper details the use of this device for measurements and troubleshooting of optical cables in an optical cable manufacturing facility. Included in this report is a detailed description of the operation and construction of the optical TDR and its use to locate fiber breaks and anomalies in standard optical cables, flat cables, and special optical cable types. How this device is used to measure optical cable lengths and cable attenuation is also discussed. Specific examples will be described which show how the optical TDR can be used to locate small-scale aberrations in an optical cable induced by abnormalities in the manufacturing process. It will be shown that the optical TDR is a very powerful and useful device in an optical cable plant environment.

*****

M. D. Rourke, S. M. Jensen, and M. K. Barnoski

Fiber parameter studies with the OTDR

In "Fiber Optics, Advanced Research and Development," Bernard Bendow and Shashanka S. Mitra, eds., Plenum Press; 1979

*****

L. Stensland and G. Borak

Precision measurements with OTDR

Digest, Colloq. Meas. Tech. for Opt. Fibre Sys., London, 8/1-8/2; 1979, IEE

*****

M. K. Barnoski, S. M. Jensen, and M. D. Rourke

OTDR differential-modal-attenuation measurements

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 133-139; 1978

The optical time-domain reflectometer has been used to continuously observe the approach of fiber attenuation to the steady-state in a graded index fiber. Data which was obtained from a 4-km continuous fiber and which shows the approach to steady-state attenuation for various launching conditions are presented.

*****

Bruno Costa, Carlo DeBernardi, and Bruno Sordo

Backscattering technique by wavelength dependent measurements

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 140-144; 1978

The wavelength dependence of the light back-scattered in an optical fibre is measured. Data on the accuracy of the attenuation measurement by the backscattering method are obtained by comparing the spectral loss curve resulting from the conventional differential method with loss values from backscattering at various wavelengths.

Finally an extensive comparison of the attenuation values obtained by the two techniques for a large number of graded index fibres is carried out.

*****

Douglas L. Franzen, B. L. Danielson, and G. W. Day

A simple first positive system nitrogen laser for use in optical fiber measurements

IEEE J. Quantum Electron. QE-14:402-404; 1978

A near infrared laser operating on several transitions of the first positive system of N_2 was developed for measurements associated with optical fibers. The laser features a simple, longitudinal, segmented design giving pulsewidths of 60 to 80 ns full width at half maximum (FWHM) and peak powers of over 600 W in the 0.86 to 0.89 μm region in addition to significant output near 1.04 and 1.23 μm. Backscatter-reflection returns from optical fibers have been obtained using the laser.

*****

E. G. Neumann

Optical time domain reflectometer: A comment

Appl. Opt. 17:1975; 1978

*****

M. K. Barnoski, M. D. Rourke, S. M. Jensen, and R. T. Melville

Optical time domain reflectometer

Appl. Opt. 16:2375-2379; 1977

By using an optical time domain reflectometer a new measurement technique which allows displaying the length dependence of the fiber attenuation by analyzing backscattered light has been developed. This paper compares the backscatter and insertion-loss techniques. In addition, results of several experiments which illustrate the versatility of an optical time domain reflectometer are described.

*****

Bruno Costa and Bruno Sordo

Experimental study of optical fibres attenuation by a modified backscattering technique

Proc., Third Eur. Conf. Opt. Commun., Munich, 69-71; 1977

A modification to the experimental arrangement of the backscattering method for the investigation of attenuation characteristics of optical fibres is proposed, that allows end fire launching of the light beam into the fibre. Advantages of this new technique are simplicity, high launching efficiency, control of launching conditions. Results are presented relative to reproducibility, accuracy, length and mode dependence of attenuation.

*****

S. D. Personick

Photon probe--an optical-fiber time-domain reflectometer

Bell Sys. Tech. J. 56:355-366; 1977

This paper describes an optical time-domain reflectometer that incorporates a gated photomultiplier receiver. The instrument can detect extremely weak reflections from fiber breaks (more than 65 dB below the 4-percent reflection of a perfect break) with 0.5-m distance resolution. In addition, backward Rayleigh scattering, which occurs roughly uniformly along a fiber, can be used to estimate the attenuation vs position within a fiber. Therefore, regions of high attenuation can be located nondestructively from one end of the fiber.

*****

M. K. Barnoski and S. M. Jensen

Fiber waveguides: A novel technique for investigating attenuation characteristics

Appl. Opt. 15:2112-2115; 1976

Light from a pulsed GaAs injection laser is coupled into a glass fiber via a taper coupler. The time dependence of the light backscattered within the fiber as the pulse travels down the waveguide is recorded. From these data the total loss may be determined, as well as an estimate of the scattering and mode mixing characteristics of the fiber.

*****

M. K. Barnoski, M. D. Rourke, and S. M. Jensen

A novel technique for investigating attenuation characteristics of fiber waveguides

Digest, Second Eur. Conf. Opt. Fibre Commun., Paris, 75-79; 1976

Light from a pulsed GaAs injection laser is coupled into a glass fiber waveguide via a taper coupler. The time dependence of the light backscattered within the fiber is recorded as the pulse travels down the waveguide. From this data the total loss may be determined, as well as an estimte of the scattering, mode-mixing characteristics, and length of the fiber. The approach can also be used to determine the location of in-line connectors or faults and the magnitude of their insertion loss.

*****

B. Hillerich

Pulse-reflection method for transmission-loss measurement of optical fibres

Electron. Lett. 12:92-93; 1976

A method for attenuation measurement of optical fibres by pulse reflections at the fibre's end is described. This method may be suitable for evaluating the attenuation of optical-fibre cables in the field.

*****

F. P. Kapron, R. D. Maurer, and M. P. Teter

Theory of backscattering effects in waveguides

Appl. Opt. 11:1352-1356; 1972

Associated with a signal transmitted down a waveguide are multiple back and forth scatterings. These produce a delayed decaying interference trailing a sharp signal pulse. An analytical description of this phenomenon enables an estimate of its effect on an optical waveguide's information-carrying capacity. For the example of a signal-to-interference ratio of 100 in a 1-km fiber of 20-dB attenuation, a bit rate limitation occurs when the fractional backscattered power captured per unit length exceeds 1.3 dB/km.

2.4 Other Methods

G. Cancellieri and M. Zoboli

Enhanced-sensitivity nondestructive measurement of optical fiber loss

Alta Freq. 47:256-259; 1978

A nondestructive method has been developed to the point where it allows the measurement of very low attenuation constants in optical fibers. A complete analysis of the relative errors shows that a substantial improvement is obtained, if the difference between two measurements of scattered power is performed electrically.

*****

F. T. Stone

Launch dependent loss in short lengths of graded-index multimode fibers

Appl. Opt. 17:2825-2830; 1978

In this paper we describe the effect of different launching conditions on the loss measured with a calorimeter in short (~1-m) lengths of multimode optical fiber. A qualitative description of the relation between the energy distribution in the fiber and various excitation variables is given, and many examples are presented that illustrate the effect that launch conditions have on the fiber loss. The use of launch-dependent loss phenomena to diagnose loss mechanisms in optical fibers is discussed. In particular, loss plots are shown for two germania-doped silica-core fibers that indicate a strong absorption loss mechanism located deep within the fiber core.

*****

F. T. Stone, B. R. Eichenbaum, and C. R. Lovelace

Loss measurements in optical ribbons using calorimetry

Appl. Opt. 17:2484-2486; 1978

*****

G. J. Cannell

Continuous measurement of optical-fibre attenuation during manufacture

Electron. Lett. 13:125-126; 1977

An online method of continuously monitoring the attenuation of an optical fibre during its manufacture is described. It provides a complete attenuation/length profile of the fibre. The present system can measure an overall attenuation of 30 dB, and the results agree with corresponding offline differential measurements to better than ±1 dB/km.

*****

L. A. Franks, M. A. Nelson, T. J. Davies, P. Lyons, and J. Golob

A technique for measuring optical fiber transmission using the time dispersion of Cerenkov radiation

J. Appl. Phys. 48:3639-3650; 1977

A technique based on measurement of time dispersion in a δ-function Cerenkov pulse has been developed for determining the attenuation coefficient $\alpha(\lambda)$ of low-loss optical fibers. The time domain amplitude distribution of the transmitted polychromatic pulse is transformed to the wavelength domain by accurate measurement of the differences in arrival times of spectral bands isolated by interference filters. Since the Cerenkov pulses are generated in the fiber by a short burst of relativistic electrons, $\alpha(\lambda)$ can be measured over a wide and continuous range of path lengths without breaking the fiber. The technique has been demonstrated over the 500-800-nm spectral region for fiber lengths up to 800 m.

*****

Walter Heitmann

Attenuation measurement in glasses for optical communications: An immersion method

Appl. Opt. 15:256-260; 1976

In fiber waveguides for optical communication losses of a few dB/km have been realized. To measure the attenuation in bulk glass rods, which are often used as starting material for fiber production, an accuracy of at least 1 dB/km is desirable. With the method reported, the losses were determined from transmission measurements on 3-cm long samples. To eliminate surface losses the samples were immersed in a liquid of about the same refractive index. For two types of synthetic vitreous silica--Suprasil 1 and Suprasil W1--the attenuation was measured between 400 nm and 750 nm. These loss-spectra show that for Suprasil 1, with the exception of the region of OH absorption, the limit of the intrinsic losses of pure silica is reached, while Suprasil W1 shows considerably higher attenuation in the whole region. The measuring accuracy achieved so far was estimated to be about ± 1 dB/km.

*****

J. A. Lewis

Laser heating of an optical fiber

Appl. Opt. 15:1304-1306; 1976

For use in absorption measurements in low-attenuation glass fibers, we calculate the periodic temperature-rise at the surface of a glass cylinder heated by a chopped laser beam. Specifically, we give the mean temperature, setting the operating temperature of the experiment, and the peak-to-peak temperature, determining the sensitivity of the measurements.

*****

K. I. White

A calorimetric method for the measurement of low optical absorption losses in optical communication fibres

Opt. Quantum Electron. 8:73-75; 1976

*****

Walter Heitmann

Attenuation measurement in low-loss optical glass by polarized radiation

Appl. Opt. 14:3047-3052; 1975

For the production of fiber waveguides suitable for optical communications cables, glasses with extremely low attenuation are required. A new method is described for measuring the optical attenuation of bulk glasses in the wavelength range of 0.4-1.1 µm. Using a quartz halogen source with highly stabilized radiation power, a linearly polarized, monochromatic, collimated beam was produced, passing the sample at the Brewster angle. Transmission loss, residual reflection, and surface scattering were measured by low-noise photodiodes and integrating digital voltmeters. A stability of 10^{-5} and a resolution of 10^{-5} or better were achieved. Results for two different kinds of commercial glasses, fused quartz (Ultrasil) and synthetic vitreous silica (Suprasil W1), are reported and discussed.

*****

D. A. Pinnow and T. C. Rich

Measurements of the absorption coefficient in fiber optical waveguide using a calorimetric technique

Appl. Opt. 14:1258-1259; 1975

*****

Irene Broquet

La diffusion dans les fibres optiques multimode (Scattering in multimode optical fibers)

Ann. Telecomm. 29:195-208; 1974

An investigation into the losses due to scattering in optical fibers has required the realization of two devices for the evaluation of these losses. One of them is an Ulbricht sphere adapted for measuring the total coefficient of attenuation by scattering. The other device permits a polar diagram of the scattering to be obtained and enables one to see how the energy is distributed in the space. The results of the measurements taken with regard to several so-called multimode fibers are presented. Several theoretical models are considered and an attempt is made to find among them those that account best for the phenomena observed.

*****

R. L. Cohen

Loss measurements in optical fibers: 1. Sensitivity limit of bolometric techniques

Appl. Opt. 13:2518-2520; 1974

A new technique for measuring the attenuation of light in clad fibers is discussed. The basic approach is to measure the temperature rise produced in the fiber by the absorption of the light. Calculations indicate that the theoretical limit of sensitivity, which should be approachable with a relatively simple experimental configuration, is a loss of about 2.5 x 10^{-7}/cm with 1 mW of light power and a 1-cm long sample. The theoretical sensitivity limit should improve with the square root of the sample length. A variation of the basic approach, which may make it possible to monitor attenuation in fibers as they are being drawn, is also discussed.

*****

R. L. Cohen, K. W. West, P. D. Lazay, and J. Simpson

Loss measurements in optical fibers: 2. Bolometric measuring instrumentation

Appl. Opt. 13:2522-2524; 1974

This paper describes two approaches to measuring transmission losses in optical fibers by the thermal-rise technique. Rapid and convenient loss determinations can be made on short (~10-cm) lengths of fibers. Values of loss as low as ~10^{-7} cm^{-1} (0.043 dB/km) can be measured with transmitted light power of ~100 mW.

*****

F. W. Ostermayer, Jr. and W. W. Benson

Integrating sphere for measuring scattering loss in optical fiber waveguides

Appl. Opt. 13:1900-1902; 1974

An integrating sphere for light scattered from fused silica optical fiber waveguides that is relatively simple to construct and easy to use is described. The novel feature is the use of a solid sphere of fused silica to facilitate coupling the scattered light out of the fiber cladding into the detector. The fiber is inserted into a slot in the sphere, and glycerine is used to index match between the fiber and sphere. The sphere is coated with high reflectivity barium sulfate, and a silicon photodiode detects the radiation in the sphere. The construction, operation, and performance tests on the sphere are described.

*****

T. C. Rich and D. A. Pinnow

Evaluation of fiber optical waveguides using Brillouin spectroscopy

Appl. Opt. 13:1376-1378; 1974

Optical scattering loss in fiber optical waveguides is the sum of the bulk material scattering and excess scattering loss due to imperfections in the waveguide structure. The recently developed Brillouin spectroscopic technique for evaluating bulk scattering has been extended to fiber waveguides, and a detailed investigation has been performed on a borosilicate clad-pure fused silica core waveguide. The technique has been found to be useful in evaluating scattering due to waveguide imperfections that have been determined to occur at the core-cladding interface. In addition to providing a measure of the waveguide scattering loss, the Brillouin technique has also been found to be useful in determining the molar composition of the borosilicate cladding glass and the partition of guided optical power between the core and cladding regions. The unusual capabilities of this technique should make it generally useful for characterizing integrated optical structures.

*****

A. R. Tynes

Integrating cube scattering detector

Appl. Opt. 9:2706-2710; 1970

The construction, calibration, and use of an integrating cube scattering detector used to measure scattering losses in optical fibers is described. The detector consists of six 1-cm sq silicon solar cells, each sensitive surface of which comprises one interior surface of a cube 1 cm on edge. Small holes in the center of two opposite faces of the cube permit the optical fiber to pass through the detector so that all the scattered light falls on a photosensitive surface.

3.1 General

I. Kobayashi

Bandwidth measurement in multimode optical fibers

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 49-54; 1980, U.S. Govt. Printing Office

*****

D. Gloge

Effects of chromatic dispersion on pulses of arbitrary coherence

Electron. Lett. 15:686-687; 1979

Chromatic signal distortion in fibre waveguides depends on the coherence of the optical carrier. The theory derived here covers carriers of arbitrary coherence and arbitrary dispersion characteristics. It gives simple estimates for the available signal bandwidth.

*****

A. H. Hartog

Influence of waveguide effects on pulse-delay measurements of material dispersion in optical fibres

Electron. Lett. 15:632-634; 1979

The effect of the waveguide structure on pulse-delay measurements of material dispersion in optical fibres is examined. It is shown that waveguide dispersion has only a small influence on the measured values and introduces an uncertainty in the wavelength of zero material dispersion of order ±3 nm.

*****

D. Marcuse

Interdependence of waveguide and material dispersion

Appl. Opt. 18:2930-2932; 1979

Theoretical work on dispersion in single-mode fibers sometimes uses the assumption that waveguide dispersion D_w and material dispersion D_m are separate effects that contribute additively to the total amount of dispersion D_{m+w}. Using Gloge's LP-mode approximation we compute the dispersion of the LP_{01} (HE_{11}) mode by solving the eigenvalue equation taking dispersion of core and cladding materials into account. The dispersion of the LP_{01} mode is computed by numerical differentiation of the solution of the eigenvalue equation. The difference $D_{m+w} - D_m$ is compared to waveguide dispersion D_w, which is computed by ignoring the dispersive properties of the core and cladding materials. We find large percentage deviation between $D_{m+w} - D_m$ and D_w. The assumption of addivity of material and waveguide dispersion is thus not quite correct. However, because of the small contribution of waveguide dispersion to the total dispersion of the LP_{01} mode, even a large percentage error in the waveguide dispersion has little influence on the over-all dispersion of the LP_{01} mode.

*****

H. M. Presby, D. Marcuse, and L. G. Cohen

Calculation of bandwidth from index profiles of optical fibers: 2. Experiment

Appl. Opt. 18:3249-3255; 1979

The impulse response and bandwidth of GeO_2-doped and B_2O_3-doped multimode optical fibers are calculated from their measured refractive index profiles. The computational method is based on the WKB solution of the guided mode problem in which the pulse delay time of each mode is determined with profile dispersion being taken into account. Accurate profiles are obtained by a newly developed focusing technique, which allows measurements to be made on whole-fiber samples. The predicted bandwidths of the GeO_2-doped fibers range from approximately 200 to 1200 MHz-km and are in good agreement with the bandwidths and impulse responses previously measured by frequency-domain and time-domain optical shuttle pulse techniques on kilometer lengths of the fibers.

*****

A. B. Sharma and S. J. Halme

Frequency response of optical fibers using a combination time-frequency domain technique

Appl. Opt. 18:1870-1879; 1979

*****

F. M. E. Sladen, D. N. Payne, and M. J. Adams

Definitive profile-dispersion data for germania-doped silica fibres over an extended wavelength range

Electron. Lett. 469-470; 1979

New results are presented for the wavelength dependence of the profile-dispersion parameter P in optical waveguides fabricated from germanosilicate glasses. These results show that P is independent of both GeO_2 concentration and thermal history of the glasses.

*****

K. Jürgensen

Gaussian pulse transmission through monomode fibers, accounting for source linewidth

Appl. Opt. 17:2412-2415; 1978

When Gaussian pulses are transmitted thorugh a monomode dielectric optical waveguide, the pulses are broadened. The total width of a received pulse consists of three components: The width of the emitted pulse and the broadening caused by dispersion in the waveguide together with both the bandwidth of the pulse and the linewidth of the source. The broadened pulses have an oscillating distortion function superimposed on them which deteriorates their resolution. The transmission capacity of an optical monomode transmission system can be calculated from the results of this paper by insertion of the appropriate parameters.

*****

E. Nicolaisen and J. J. Ramskov-Hansen

A novel technique for investigating dispersion characteristics of fiber waveguides

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 171-178; 1978

A new experimental technique for measuring the differential phase is presented along with results demonstrating excellent agreement between time and frequency domain measurements. Calculated curves of the delay distortion will also be given for comparison.

*****

J. J. Ramskov-Hansen and E. Nicolaisen

Propagation in graded index-fibers: Comparison between experiment and three theories

Appl. Opt. 17:2831-2835; 1978

We compare the measured impulse response of a graded-index fiber by three different theories: the WKB method applied for an arbitrary profile; the α-profile approximation; and perturbation theory. We find that the WKB method gives both a qualitatively and quantitatively good agreement. The perturbation theory gives a qualitatively good calculation of the width of the impulse response (the dispersion). The α-profile approximation gives a very poor result. We also investigate the influence of the launching conditions on the impulse response and find that the dispersion for this fiber decreases with the excitation of higher order modes. This is found to be in agreement with the WKB theory.

*****

I. W. Sandberg, I. P. Kaminow, L. G. Cohen, and W. L. Mammel

On the phase of the modulation transfer function of a multimode optical-fiber guide

Bell Sys. Tech. J. 57:99-109; 1978

We consider the range of validity of a Hilbert-transform approach in which the measured magnitude of the modulation-transfer-function of an optical fiber is used to compute the fiber's impulse response. It is argued that a key "minimum-phase assumption" can fail to be satisfied in important cases, and a few closely related experimental and analytical results are presented.

*****

I. W. Sandberg

A note concerning optical-waveguide modulation transfer functions

Bell Sys. Tech. J. 57:3047-3057; 1978

A necessary and sufficient condition is given for the modulation-transfer-function of certain multimode optical fiber guides to be zero free in the closed right-half of the complex plane, and to be structurally stable with respect to that property. The condition is of interest, for example, in connection with the possibility of determining the phase of a modulation-transfer-function from its amplitude.

*****

E. J. Bochove and A. Cozannet

Low-pass filter characteristics of multimode graded index fibres

Opt. Quantum Electron. 9:135-141; 1977

On the basis of ray model solutions, the response of a lossless multimode graded-index fibre to a modulated source is calculated. The results demonstrate great sensitivity of the bandwidth of the fibre to small variations in index profile.

*****

Mashiro Ikeda and Kenichi Kitayama

Transmission characteristics of mode scrambler loaded long length spliced graded index fibers

Tech. Digest, IOOC-77, Tokyo, 419-422; 1977

Transmission characteristics of long length spliced graded index fibers are described. The spliced transfer function has been determined by the condition that the fiber is excited by the steady state mode exciter and the mode scramblers are loaded just after all splices. Under these conditions, the spliced transfer function presumed by the unit transfer function is in good agreement with the measured transfer function. It has been found that, transmission band width can be widened by loading the mode scramblers.

*****

Charles Vassallo

Linear power responses of an optical fiber

IEEE Trans. Microwave Theory Tech. MTT-25:572-576; 1977

It is known that an optical fiber behaves linearly in terms of power when the modulation frequency is smaller than the spectrum width of the light source. In order to calculate the impulse or frequency power responses with a modal calculation, it is shown that the powers carried by the different modes are independent in usual cases. Different formulas are proposed for the linear responses when there is no mode coupling, and the corresponding validity conditions are given.

*****

Bruno Crosignani and Paolo DiPorto

Propagation of coherence and very high resolution measurements in optical fibers

SPIE 77:49-56; 1976

Two methods for measuring the dispersion associated with propagation of different modes in guiding structures are presented. While the usual measurements are based on the direct observation of the distortion undergone by propagating pulses, in the first method one obtains information on the delays among the different modes by observing the changes of the coherence properties of a continuous signal. In the second method, one observes the temporal variation of the output intensity once the input signal has been frequency modulated. These methods allow one to appreciate time differences of the order of some picoseconds, so that sufficient delays can be obtained over short fiber lengths. Experiments are illustrated in which delays of this order of magnitude have been actually measured.

*****

James P. Wittke

Dispersion-limited modulation bandwidths of optical fibers

RCA Rev. 35:198-215; 1974

The information-carrying capacity of an optical fiber is often limited by dispersive effects in the fiber. For relatively short transmission paths (under 500 meters) modal dispersion, caused by the difference between group velocities of the different propagating modes, is dominant. Measurements of the modulation transfer functions of three types of optical fiber, two step-index filters and a graded-index fiber, have been made using both frequency- and time-domain techniques. A simple ray model predicts many of the properties of the lowest-loss step-index fiber, while the assumption of strong attenuation in the higher-order modes is necessary to explain the data on the high-aperture step-index fiber. The graded-index fiber shows anomalously large pulse broadening.

*****

D. Gloge

Dispersion in weakly guiding fibers

Appl. Opt. 10:2442-2445; 1971

Optical signals transmitted through cladded glass fibers are subject to delay distortion because of (1) dispersion in the material, (2) dispersion caused by the waveguide characteristic, and (3) delay differences between modes. We isolate these effects and evaluate their significance for cases of practical interest. These concern fibers in which the refractive index of the cladding is only slightly lower than that of the core.

3.2 Time Domain Methods

E. F. Anderson

Differential propagation delay in optical multifibre cables

Electron. Lett. 16:389-391; 1980

Pulse propagation delays in different GI-fibres within a cable have been measured as a function of temperature between -15° and +50°C. Two types of optical cables have been tested. Variation in propagation delay differences between fibres of up to 0.65 ns/km were observed.

*****

M. J. Buckler

Optimization of concatenated fiber bandwidth via differential mode delay

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 59-62; 1980, U.S. Govt. Printing Office

*****

M. J. Buckler, J. W. Shiever, and F. P. Partus

Optimization of multimode fiber bandwidth via differential group delay analysis

Digest, Sixth Eur. Conf. Opt. Commun., York, 33-36; 1980, IEE

*****

M. Horiguchi, Y. Ohmori, and H. Takata

Profile dispersion characteristics in high-bandwidth graded-index optical fibers

Appl. Opt. 19:3159-3167; 1980

To study profile dispersion effects on transmission bandwidth in high-bandwidth graded-index fibers, baseband frequency responses of various graded-index fibers with different profile parameters have been characterized in the 0.78-1.50-μm wavelength range. The test graded-index fibers were made by the MCVD technique. Intrinsic intermodal dispersions of these fibers were determined using a combination of a GaAlAs laser and a grating monochromator, a mode-locked Nd:YAG laser, an InGaAsP/InP laser, and stimulated Raman scattering in a single-mode fiber as the light sources. Transmission bandwidth functional dependences on wavelength are presented. The transmission bandwidth of the individual functional dependences on wavelength are presented. The transmission bandwidth of the individual fibers changed by more than 400% within the experimental spectral range. The maximum transmission bandwidth so far observed was 3.74 GHz-km at 1.225-μm wavelength for a fiber with 0.20 N.A. Transmission bandwidth spectra were compared with computer calculated results based on Olshansky's theory.

*****

Chinlon Lin, Leonard G. Cohen, William G. French, and Herman M. Presby

Measuring dispersion in single-mode fibers in the 1.1-1.3 μm spectral region--A pulse synchronization technique

IEEE J. Quantum Electron. QE-16:33-36; 1980

We describe a novel technique for measuring dispersion in low-loss single-mode fibers in the 1.1-1.3 μm spectral region. The spatial equivalent of the pulse delay time as a function of wavelength is obtained in the measurement. The technique makes use of the wavelength-dependent pulse synchronization condition in a pulse-pumped near IR fiber Raman oscillator. Experimental results on three single-mode germanium-doped silica fibers are compared, and the importance of matching the minimum dispersion wavelength with the local loss minimum in fiber design is discussed.

*****

W. F. Love

Bandwidth spectral characterization of GeO_2-P_2O_5-SiO_2 multimode optical waveguides

Digest, Sixth Eur. Conf. Opt. Commun., York, 113-116; 1980, IEE

*****

J. Piasecki

Subpicosecond measurement of response of optical fibres

Electron. Lett. 16: 498-500; 1980

A novel technique is described for measuring the impulse response of short samples of monomode and multimode optical fibres, with a resolution better than 0.1 ps. The times of arrival of the modes of a multimode fibre are resolved.

*****

H. F. Schlaak and M. Gwiazdowski

Ein optisches Faserlangenmessgerat und dessen Eigneschaften (An optical fiber length measurement apparatus and its characteristics)

Digest, Mess. in der opt. Nachrichten., Berlin, 22-29; 1980 VDE-Verlag

*****

S. Seikai and K. Fussgaenger

Experimental method for the separation of material and modal dispersion of optical fibres

Digest, Sixth Eur. Conf. Opt. Commun., York, 173-176; 1980, IEE

*****

S. Seikai and K. Fussgaenger

Experimental method for the separation of material and modal dispersion of optical fibres

Digest, Mess. in der opt. Nachrichten., Berlin, 98-101; 1980, VDE-Verlag

*****

Nori Shibata, Mitsuhiro Tateda, Shigeyuki Seikai, and Naoya Uchida

Spatial technique for measuring modal delay differences in a dual-mode optical fiber

Appl. Opt. 19:1489-1492; 1980

A simple spatial method using a coherent light source and an interferometer is proposed for measuring the group delay time difference between the LP_{01} and LP_{11} modes in a dual-mode optical fiber. Experimental results obtained by this method are in good agreement with those obtained by the swept-frequency and pulse methods. Moreover, a group delay time difference of 4 psec is measured. Results suggest that this spatial method can be applied to a short fiber less than 1 m in length and/or small time differences around 1 psec by using a laser diode with a short coherence length.

*****

Douglas L. Franzen and G. W. Day

Measurement of optical fiber bandwidth in the time domain

NBS Technical Note 1019, U.S. Govt. Printing Office; 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.

*****

B. Costa, F. Esposto, and B. Sordo

Wavelength dependence of differential group delay in graded-index optical fibers: Application to fiber-links characterization

Tech. Digest, Opt. Fiber Commun., Washington, 122-125; 1979, Opt. Soc. Am.

*****

Douglas L. Franzen and Gordon W. Day

Measurement of propagation constants related to material properties in high-bandwidth optical fibers

IEEE J. Quantum Electron. QE-15:1409-1414; 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.

*****

P. Geittner

Dispersion measurements on PCVD optical fibres using a mode locked synchronously pumped dye laser system

Proc., Opt. Commun. Conf., Amsterdam, 14.2-1--14.2-4; 1979

The use of a mode locked synchronously pumped dye laser system allows a very detailed and almost complete characterization of the dispersion characteristics of optical fibres. Profile and material dispersion as well as profile disturbances, homogeneity, actual and optimum α-parameters of the fibres can be selectively determined as a function of wavelength. First experimental results on PCVD fibres confirm the high quality of the PCVD production process.

*****

Chinlon Lin, L. G. Cohen, W. G. French, and H. M. Marcuse

Measuring dispersion in single-mode fibers in the 1.1-1.3 μm spectral region--A pulse synchronization technique

Proc., Opt. Commun. Conf., Amsterdam, 14.3-1--14.3-5; 1979

We describe a novel technique for measuring dispersion in low-loss single-mode fibers in the 1.1-1.3 μm spectral region. The spectral equivalent of the pulse delay time as a function of wavelength is obtained in the measurement. Measurement results on three single-mode germanium-doped silica fibers are compared, and the importance of matching the minimum dispersion wavelength with the local loss minimum is discussed.

*****

Katsunari Okamoto

Comparison of calculated and measured impulse responses of optical fibers

Appl. Opt. 18:2199-2206; 1979

The principal purpose of this paper is to compare calculated and measured impulse responses of multimode optical fibers to substantiate the validity of the theoretical approach now being used by investigators. To perform the comparison efficiently, a new, practical method of analysis of the impulse response of inhomogeneous optical fibers is presented first. The necessary input data for calculating the impulse response are refractive indices at N points, refractive index in the cladding, core radius, and the wavelength of the light source. The calculated impulse responses are compared with the measured ones for several multimode optical fibers, showing good agreement.

*****

Michael E. Padgett and Sedki M. Riad

Optical fiber dispersion characterization study at Kennedy Space Center

Proc., Fiber Opt. Commun.-79, Chicago, 63-66; 1979, Information Gatekeepers

An optical fiber dispersion characterization test set was developed at Kennedy Space Center with the aid of the University of Central Florida, Orlando, Florida. This development included the test algorithm development, hardware design, and signal processing software implementation for an HP-9825 computer. To date, the dispersion characterization test was run on fibers up to 2.4 Km in length. Test results showed that the impulse response of the 2.4 Km fiber has a 0.675 ns full duration at half the maximum value (FDHM), which corresponds to an FDHM dispersion of 0.28 ns/Km. Also, the 3dB bandwidth of the 2.4 Km fibers is 560 MHz, which corresponds to 1.34 GHz·Km fiber bandwidth capacity (bandwidth-length product). Test set modifications are planned to allow testing of fiber lengths of up to 8 Km.

*****

Harish R. D. Sunak

Pulse dispersion measurements in conventional Selfoc fibers

Appl. Opt. 18:1106-1109; 1979

Measurements of pulse dispersion in conventional Selfoc fibers have been carried out. The principal light source was a pulsed mode-locked ruby laser. Qualitative agreement has been found with theory, which predicts multimode operation and, hence, large pulse dispersion in such fibers under greatly mismatched launching conditions. Under such conditions, we have observed dispersion equivalent to ~20 nsec/km.

*****

B. Rehfeld

Measurement tehcnique of the transfer function of fibers in optical communication cables

Conf. Rec., Int. Conf. Commun., Boston, 36.6.1-36.6.4; 1979, IEEE

A transmission path can be completely described by the baseband function $\underline{H}$ (ω). Therefore, it is also used to specify the baseband-related transmission properties of optical fibers in optical cables. The attenuation and the group delay distortions can be derived from the baseband transfer function. The values submitted in this paper were measured on optical cables of the local network of West Berlin.

*****

K. F. Barrell, D. J. Carpenter, and C. Pask

Interpretation of optical-fibre baseband frequency measurement

IEE J. Microwave Opt. Acoust. (UK) 2:41-44; 1978

The excitation of optical fibres by a focused laser beam is described and the particular modes excited are identified. The results are used to reanalyze an experiment on baseband frequency measurement. Misconception in the original analysis concerning the role of the source are pointed out.

*****

K. Behm

Dispersion measurement of CVD-fabricated fibres with a finite number of layers

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 64-70; 1978

The graded index profiles of fibres which are produced by the CVD-method have stairlike perturbations because of a finite number of layers. Furthermore germanium doped fibres exhibit an additional index oscillation in each layer. The influence of these profile perturbations on fibre dispersion has been investigated experimentally and theoretically. For the example of a germanium doped fibre with a 50 μm diameter core and a NA of 0.23 we conclude that the core should contain at least 35 layers, if a total pulse broadening of 3 ns/km and a 3-dB width broadening of 0.4 ns/km is allowed. For minimal dispersion, however, it should consist of more than 200 layers.

*****

Leonard G. Cohen and Chinlon Lin

A universal fiber-optic (UFO) measurement system based on a near-IR fiber Raman laser

IEEE J. Quantum Electron. QE-14:855-859; 1978

A universal fiber-optic measurement system, which is useful for measuring loss and dispersion in the 1.06-1.6 μm wavelength region, is described. The source is a silica fiber Raman laser pumped by a mode-locked and Q-switched Nd:YAG laser at 1.06 μm. Subnanosecond multiple-Stokes pulses in the 1.1-1.6 μm wavelength region are generated in a low-loss single-mode silica fiber. The use of this near-infrared fiber Raman laser for characterizing various transmission properties of single and multimode test fibers is demonstrated. Loss spectra, intramodal dispersion, and intermodal dispersion data are obtained in the wavelength region of minimum loss and minimum loss and minimum material dispersion for silica fibers.

*****

L. Jeunhomme, J. P. Pocholle, and J. Raffy

Wavelength dependence of modal dispersion in graded index optical fibres

Electron. Lett. 14:364-366; 1978

We describe a method based on the selective mode excitation at different wavelengths for studying the profile dispersion influence on the modal dispersion. By using this technique, we are able to determine either the optimum wavelength at which the fibre should be operated or the correction needed for optimising the index profile at a given wavelength.

*****

Chinlon Lin, L. G. Cohen, W. G. French, and V. A. Foertmeyer

Pulse delay measurements in the zero-material-dispersion region for germanium- and phosphorus-doped silica fibres

Electron. Lett. 14:170-172; 1978

Wavelength-dependent pulse dispersion in germanium- and phosphorus-doped silica fibres of different concentration was measured using mode-locked subnanosecond pulses in the 1.064-1.55 μm wavelength range. Zero dispersion for GeO_2SiO_2 fibres was observed in the 1.3-1.33 μm region depending on the concentration. P_2O_5-doped silica fibres showed zero dispersion near 1.28 μm, independent of doping concentration.

*****

Takonori Okoshi and Katsuro Sasaki

Precise measurement of the impulse response of an optical fiber

Trans. IECE Japan, E61:964-965; 1978

By refining the deconvolution technique proposed previously by the same authors for determining the impulse response of optical fibers, the time resolution has been improved. In some cases an impulse response consisting of several independent pulses is obtained; probably these pulses correspond to separate LP-mode groups.

*****

D. N. Payne and A. H. Hartog

Pulse delay measurement of the zero wavelength of material dispersion in optical fibres

Nachrichtentech. Z. (Germany) 31:130-132; 1978

Pulse delay measurements on fibres are reported over a wide wavelength range straddling the zero of material dispersion. Results for phosphosilicate and a range of germania-doped fibres indicate that the wavelength of negligible material dispersion lies in the range 170--1350 nm. The optimum wavelength depends on the concentration for fibres containing germania.

*****

F. M. E. Sladen, D. N. Payne, and M. J. Adams

Profile dispersion measurements for optical fibres over the wavelength range 350 nm to 1900 nm

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 48-57; 1978

*****

B. Sordo, F. Esposto, and B. Costa

Experimental study of modal and material dispersion in spliced optical fibres

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 71-78; 1978

Material dispersion in spliced graded index fibres is measured and found to follow a linear addition law. Measurements of pulse dispersion in spliced fibres show that best combinations can be found that minimize total pulse dispersion, when dealing with near optimum profile fibres. Evidence of pulse compression effects with a GaAlAs laser is reported.

*****

R. Olshansky and S. M. Oaks

Differential mode delay measurement

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 128-132; 1978

A differential mode delay (DMD) measurement has been developed to analyze the detailed features of pulse broadening in graded-index optical waveguides. DMD data can be interpreted directly in terms of deviations from the optimal alpha profile, α_0, and is sensitive to small profile changes. The measurement thus appears to be a fast, practical alternative to direct profile measurement.

*****

Karl Behm

Dispersion measurement of CVD-fabricated fibers with a refractive index dip on the fibre axis

Proc., Third Eur. Conf. Opt. Commun., Munich, 28-30; 1977

A series of graded index fibres with varying index dips have been fabricated and their dispersion has been measured. The output pulse shows a distortion which is typical for this profile perturbation and may deteriorate optical communication at high bit rates considerably. Technologies to reduce the dip are discussed.

*****

C. Boisrobert, A. Cozannet, P. Lamouler, L. Martin, H. Diraison

Mesure des distorsions de temps de propagation de groupe sur les fibres optiques a saut d'indice (Measurement of group delay distortion in step index fibers)

Proc., URSI, Meas. in Telecomm., Lannion, 445-447; 1977

*****

Remy Bouillie, Jean-Claude Bizeul and Marcel Guibert

Response en frequence des fibres optiques: Resultats experimentaux (Frequency response of optical fibers: Experimental results)

An. Telecomm. 32:149-157; 1977

The authors discuss measurements and results performed on the transfer function of graded and step index fibres. The principles and the set up are at first described: they measure the amplitude of the transfer function by means of fine recurrent pulses, the spectra of which are compared by spectral analysis before and after their passage through the fibre. The experimental results will be compared with theoretical studies; then the influences of different parameters such as numerical aperture, index profile, mode conversion. . .will be discussed. A law is established which gives the transfer function of spliced fibres. This law is experimentally verified up to 12 kilometers. From these results they draw some conclusions on the performances of these fibres for digital transmission.

*****

L. G. Cohen and Chinlon Lin

Pulse delay measurements in the zero material dispersion wavelength region for optical fibers

Appl. Opt. 16:3136-3139; 1977

Subnanosecond pulses in the 1120-1550-nm region are generated by multiple-order stimulated Raman scattering in a small core single-mode silica fiber pumped by a Q-switched and mode-locked Nd:YAG laser at 1064 nm. These near ir pulses are injected into various km long test fibers, and relative time delay changes between different wavelengths are used to determine dispersion in a region where fiber material dispersion is small. Zero material dispersion has been observed in germanium and boron-doped single-mode and multimode test fibers.

*****

W. Eickhoff and O. Krumpholz

Pulse response and microbending losses of an optical glass-fibre waveguide with a bump in its index profile

Electron. Lett. 13:256-257; 1977

It is shown that a short light pulse is spilt into two separate output pulses when transmitted through a graded-index fibre with a refractive-index bump in its centre. For the fibre investigated, the bump acts as a monomode waveguide. This monomode waveguide turned out to be much less sensitive to microbending than the multimode graded-index waveguide, which is in agreement with existing theories.

*****

K. Inada, R. Yamauchi, T. Yamada, H. Hashimoto, S. Tanaka, and N. Uchida

Bandwidth change of graded and step index optical fibers under production process and splicing

Proc., Third Eur. Conf. Opt. Commun., Munich, 31-34; 1977

*****

D. N. Payne and A. H. Hartog

Determination of the wavelength of zero material dispersion in optical fibers by pulse-delay measurements

Electron. Lett. 13:627-629; 1977

Pulse-delay measurements on fibres are reported, made over a wide wavelength range straddling the zero of material dispersion. Results for phosphosilicate and a range of germania-doped fibres indicate that the wavelength of negligible material dispersion lies in the range 1270-1400 nm. The optimum wavelength depends on the concentration for fibres containing germania.

*****

Tadatoshi Tanifuji and Masahiro Ikeda

Pulse circulation measurement of transmission characteristics in long optical fibers

Appl. Opt. 16:2175-2179; 1977

A pulse circulation method to measure the length dependence of transmission characteristics in optical fibers is described. In principle, the method has the advantage that no unnecessary power is branched off in the loop. Using this method, the length dependence of transmission characteristics of step and graded index fibers has been measured and found to be different in both cases. It is concluded that the difference is due to the material dispersion effect, which significantly influences pulse spreading in long length graded index fibers.

*****

J. V. Wright and B. P. Nelson

Pulse compression in optical fibres

Electron. Lett. 13: 361-363; 1977

A shift in the emission wavelength of s.h. GaAs lasers has been observed during individual pulses. In conjunction with material dispersion, this leads to pulse compression after transmission through an optical fibre. The use of this device as a source in bandwidth measurements readily leads to erroneous conclusions when results are analysed.

*****

Y. Ueno, S. Aoki, and Y. Ohgushi

Material dispersion measurement of an optical fiber by FM radar method

IEEE J. Quantum Electron. QE-13:18D-19D; 1977

*****

L. G. Cohen

Pulse transmission measurements for determining near optimal profile gradings in multimode borosilicate optical fibers

Appl. Opt. 15:1808-1814; 1976

Dispersive differences between B_2O_3 and SiO_2 constituents make nonparabolic profiles optimal equalizers of intermodal group delays in fibers with graded B_2O_3-SiO_2 cores and uniform B_2O_3-SiO_2 cladding. Pulse dispersion measurements were correlated with profile shapes in a systematic study of multimode fibers with near power law gradients. Far field spatial ray filters were used to diagnose impulse response shapes so that new fibers could be fabricated with closer-to-optimal profile gradients. One of the fibers had an $\alpha \approx 1.77$ power law exponent that was nearly optimal for $\lambda = 907.5$ nm wavelength and caused $2\sigma = 0.26$-nsec/km full rms output pulse spreading. When expected material dispersion effects were deconvolved from the output pulse spreading, the resultant pulse width was approximately 75 times less than the result expected for a comparable step-index fiber. This is the largest pulse width reduction reported yet.

*****

Jurgen W. Dannwolf, Samuel Gottfried, G. Arthur Sargent, and Robert C. Strum

Optical-fiber impulse response measurement system

IEEE Trans. Instrum. Meas. IM-25:401-406; 1976

This paper describes time-domain instrumentation that was designed to measure impulse response and delay of multimode optical fibers that are being used in an experimental optical communications system at Bell Laboratories. Time-domain data is transformed to frequency-domain by a minicomputer, and the result is displayed as the fiber's baseband frequency response.

*****

I. G. Goyal, A. Kumar, and A. K. Ghatak

Calculation of bandwidth of optical fibres from experiments on dispersion measurement

Opt. Quantum Electron. 8:80-82; 1976

*****

J.-P. Hazan and L. Jacomme

Characterizing optical fibres; a test bench for pulse dispersion

Philips Tech. Rev. 36:211-216; 1976

*****

Robert Olshansky and Donald B. Keck

Pulse broadening in graded-index optical fibers

Appl. Opt. 15:483-491; 1976

This paper reports on some theoretical and experimental investigations of the radial refractive index gradient that maximizes the information-carrying capacity of a multimode optical waveguide. The primary difference between this work and previous studies is that the dispersive nature of core and cladding materials is taken into consideration. This leads to a new expression for the index gradient parameter α_c which characterizes the optimal profile. Using the best available refractive index data, it is found that in high-silica waveguides, the dispersive properties of the glasses significantly influence the pulse broadening of near-parabolic fibers, and that the parameter α_c must be altered by 10-20% to compensate for dispersion differences between core and cladding glasses. These predictions are supported by pulse broadening measurements of two graded-index fibers. A comparison is made between the widths and shapes of measured pulses and pulses calculated using the WKB approximation and the near-field measurements of the index profiles. The good agreement found between theory and experiment not only supports the predictions made for the value of α_c, but demonstrates an ability to predict pulse broadening in fibers having general index gradients.

*****

T. A. Orofino and F. C. Unterleitner

Optical fibers for dispersion in the time domain

Appl. Opt. 15:1907-1909; 1976

*****

L. G. Cohen

Shuttle pulse measurements of pulse spreading in an optical fiber

Appl. Opt. 14:1351-1360; 1975

Partially transparent mirrors were pressed against fiber ends so that length dependence of pulse spreading could be determined without cutting the fiber into pieces. Measurements were made by comparing the widths of laser pulses (λ = 0.9 μm) through the output end mirror, which returned from 9-1/2 successive round trips (2014-m extrapolated length) along a 106-m multimode fiber. Mode mixing was significant in this fiber fabricated by Corning Glass Works), and a square root of length pulse width dependence was observed. However, some of the mode-mixing effects on pulse width were caused by the way in which the fiber was wound on a drum.

*****

L. G. Cohen and S. D. Personick

Length dependence of pulse dispersion in a long multimode optical fiber

Appl. Opt. 14:1357-1360; 1975

Shuttle pulse measurements performed on a 1280-m long multimode optical fiber were used to determine pulse dispersion along a 6400-m extrapolated length. The fiber's steady-state mode coupling length was determined without breaking the fiber. The impulse responses for one, three, and five trips thorugh the fiber were recorded and Fourier transformed to yield the corresponding baseband frequency responses. It was concluded that the coupling length was approximately 840 m, and that the impulse response became increasingly more symmetrical for fiber lengths beyond this coupling length. This agrees with theory.

*****

L. G. Cohen and H. M. Presby

Shuttle pulse measurements of pulse spreading in a low loss graded-index fiber

Appl. Opt. 14:1361-1363; 1975

Shuttle pulse measurements in a multimode optical fiber were used to determine pulse dispersion, at λ = 0.9-μm wavelength, in eight increments from 148-m to 2516-m extrapolated length. There was relatively little mode mixing in this low loss fiber (minimum loss = 1.7 dB/km at λ = 1.04 μm), and the observed pulse width was primarily due to the grading of the refractive-index profile.

*****

B. P. Nelson and J. R. Stern

Pulse propagation measurements on slightly overmoded glass fibres

Proc., First Eur. Conf. Opt. Fibre Commun., London, 13-15; 1975, IEE

*****

R. W. Dawson

Pulse widening in a multimode optical fiber excited by a pulsed GaAs LED

Appl. Opt. 13:264-265; 1974

A 1-km length of low-loss multimode optical fiber made by Corning Glass Works was excited by the pulsed output of a GaAs LED. The pulses were 3.6 nsec wide and had a spectral width of 460 Å. After traveling through the fiber, the pulse had a half-power width of 6 nsec, of which 4.2 nsec was estimated to be due to material dispersion.

*****

D. Gloge, E. L. Chinnock, and T. P. Lee

GaAs twin-laser setup to measure mode and material dispersion in optical fibers

Appl. Opt. 13:261-263; 1974

Two synchronously self-pulsing GaAlAs lasers, emitting at slightly different wavelengths, are combined in a setup which evaluates mode and material dispersion in multimode fibers. The results show that material dispersion which causes a pulse broadening of 3.6 ns/km, which may represent a serious limit to the bit rates achievable in a multimode fiber system using an LED source.

*****

S. D. Personick, W. M. Hubbard, and W. S. Holden

Measurements of the baseband frequency response of a 1-km fiber

Appl. Opt. 13:266-268; 1974

Typical light-emitting diodes have a spectral width between 300 Å and 500 Å. This is sufficient to cause significant pulse broadening as a result of material dispersion in a long optical glass fiber. An experiment was performed to measure the magnitude of this effect in a fiber of 1-km length. The experiment measures the average intensity transfer function of the fiber.

*****

C. A. Burrus, E. L. Chinnock, D. Gloge, W. S. Holden, Tingye Li, R. D. Standley, and D. B. Keck

Pulse dispersion and refractive-index profiles of some low-noise multimode optical fibers

Proc. IEEE 61:1498-1499; 1973

The refractive-index profile and impulse response of three low-loss multimode optical fibers have been measured. Pulse dispersion of about 1.5 ns or less was observed in two of the fibers, each 1 km long.

*****

E. L. Chinnock, L. G. Cohen, W. S. Holden, R. D. Standley, and D. B. Keck

The length dependence of pulse spreading in the CGW-Bell-10 optical fiber

Proc. IEEE 61:1499-1500; 1973

Previous measurements of pulse broadening in the CGW-Bell-10 optical fiber showed very low dispersion (< 2 ns/km). We recently measured pulse spreading as a function of length in this fiber. The data indicate a $(\text{length})^{1/2}$ dependence, at wavelengths of 0.6328, 0.9, and 1.06 µm, for long fiber lengths (>550 m) which are of practical significance.

*****

S. D. Personick

Baseband linearity and equalization in fiber optic digital communication

Bell Sys. Tech. J. 52:1175-1195; 1973

If a sequence of digitally on-off modulated optical pulses is injected into a dielectric waveguide, these pulses may begin to overlap after a sufficient distance of propagation because of material dispersion and/or group delay spreading. In general, the pulses will not add linearly in power, which can complicate the problem of equalization of the square-law (power) detected overlapping output pulses at baseband. This paper illustrates important situations in which the guide may be treated as "pseudo-linear" in power, meaning that the detected guide output pulses appear to add linearity.

*****

D. Gloge and E. L. Chinnock

Fiber-dispersion measurements using a mode-locked krypton laser

IEEE J. Quantum Electron. QE-8:852-854; 1972

Mode delay and material dispersion limit the signal bandwidth of potential fiber communication systems. 200-ps pulses from a krypton laser, mode-locked at three different wavelengths, prove to be adequate for measuring both effects in relatively short fibers (33 m). The results are in good agreement with theory.

*****

D. Gloge, E. L. Chinnock, R. D. Standley, and W. S. Holden

Dispersion in a low-loss multimode fibre measured at three wavelengths

Electron. Lett. 8:527-529; 1972

Short pulses from mode-locked lasers (neodymium/yttrium-iron-garnet and krypton) were used to measure mode and material dispersion in 20 m of a multimode fibre at 1060, 647 and 568 nm. Uniform illumination of the cone of acceptance at the input caused a 200 ps pulse to broaden to 400 ps.

*****

D. Gloge and E. L. Chinnock

Study of pulse distortion in Selfoc fibres

Electron. Lett. 8:526-527; 1972

A 100 ps gallium-arsenide laser pulse was observed to increase in width by only 100 ps in 70 m of a fibre with an internal refractive-index gradient (Selfoc). This is shown to be in satisfactory agreement with a simple ray analysis which neglects the index discontinuity at the fibre wall.

3.3 Frequency Domain Methods

Tsuneo Horiguchi, Tadatoshi Tanifuji, and Masamitsu Tokuda

Baseband frequency response of a graded-index fiber excited by a step index fiber

Appl. Opt. 19:2589-2596; 1980

Input modal power distribution and baseband frequency response of a graded-index fiber have been investigated theoretically and experimentally, when the fiber was excited by a step-index fiber. It is found that the bandwidth of the graded-index fiber is measured with good reproducibility and accuracy by using the step-index fiber as an exciter. An appropriate choice of step-index fiber parameters is made with respect to the test graded-index fiber.

*****

L. Jeunhomme and P. Lamouler

Intermodal dispersion measurements and interpretation in graded-index optical fibres

Opt. Quantum Electron. 12:57-59; 1980

We describe in this paper a frequency-domain measurement configuration allowing the determination of intermodal dispersion, differential mode attenuation and mode-coupling effects in graded-index optical fibres. Attention is mainly given to intermodal dispersion which is obtained with a resolution of 5 ps km^{-1} and a dynamic range of 15 dB. Spatial (or modal) resolution is examined from both the theoretical and experimental point of view and the high degree of resolution of the experiment is illustrated. Interpretation of the results for deducing the index profile errors and correcting the preform manufacturing process shows the usefulness of the method for improving fibre quality.

*****

Mitsuhiro Tateda, Shigeyuki Keikai, and Naoya Uchida

Frequency characteristics of graded-index fibers

Appl. Opt. 19:765-759; 1980

Frequency response of graded-index multimode fibers, whose index profile parameter α deviates from the optimum value, is investigated both theoretically and experimentally. The frequency response of the fiber with optimum α diverges periodically. However, that of the fiber with nonoptimum α does not exhibit periodic divergence but has periodic curvature changing points whose period is inversely proportional to the amount of α deviation. The period is about a fifth of the divergence period of the fiber with optimum α when the α deviation is 0.1. The optimum α difference between λ = 0.82 and 1.27 µm is found to be 0.07 for $GeO_2P_2O_5$-doped silica fibers by measurement of frequency responses at these wavelengths.

*****

G. Cancellieri and M. Mezzetti

Scanning technique for investigating optical fibre dispersion

Opt. Quantum Electron. 11:305-317; 1979

Differential mode delay measurements have been perfomed, both for step-index and for graded-index fibres, using a sinusoidally modulated optical source. From a differential mode delay measurement, it is possible to get all the information on the fibre baseband response with or without the effect of skew rays, and in particular of leaky rays. A theoretical model of mode coupling is developed and is used for computing the baseband response for fibres where mode coupling is not negligible.

*****

G. Cancellieri, M. Mezzetti, C. G. Someda, and M. Zoboli

Simplified procedure for indirect tests of optical-fibre transfer function

Electron. Lett. 15:234-236; 1979

Differential mode delays and attenuations are measured by scanning the fibre output field, at one source modulation frequency. The results allow a simple evaluation of the baseband transfer function. A cylindrical lens can be used to simplify the data collection.

*****

L. Jeunhomme, P. Lamouler, and F. Alard

Frequency domain determination of intermodal dispersion in graded index optical fibres

Proc., Opt. Commun. Conf., Amsterdam, 12.1-1--12.1-4; 1979

*****

S. Machida, N. Imoto, and Y. Ohmori

Multimode fibre baseband frequency response measurement with single frequency output extracted from modulated InGaAsP laser

Electron. Lett. 15:607-609; 1979

A new method to measure multimode fibre frequency response is presented by using a single longitudinal mode extracted from modulated semiconductor laser output. Intensity fluctuation noise, caused by r.f. modulation, is utilised as a broadband baseband signal. Baseband frequency response of a 1.98 km graded-index fibre is measured up to 1.5 GHz in 1.1-1.5 μm wavelength region. This method provides a simple and accurate measurement of intermodal dispersion excluding chromatic dispersion effect.

*****

Akira Sugimura and Kazuhiro Daikoku

Wavelength dispersion of optical fibers directly measured by "difference method" in the 0.8-1.6 μm range

Rev. Sci. Instrum. 50:343-346, 1979

A novel technique to measure the wavelength dispersion of optical fibers in the 0.8-1.6 μm range, where germanium avalanche photodiodes possess adequate quantum efficiency, is described. Dispersion is defined as $d\tau/d\lambda$, which can safely be changed to the difference formula $\Delta\tau/\Delta\lambda$, when $\Delta\tau$ is small, where τ is the transit time of the wave and λ is the light wavelength. A monochromatic light, whose amplitude is modulated by a sinusoidal baseband signal, is launched into the optical fiber. The phase of the sinusoidal baseband signal changes with the monochromatic light wavelength variation due to the dispersion of the fiber. The phase variation gives an accurate value of $\Delta\tau$. The wavelength dispersion is obtained directly from the values of both $\Delta\tau$ and $\Delta\lambda$. Using this technique, the wavelength dispersion of a single mode optical fiber, for example, is measured in the single mode wavelength range from 0.92 to about 1.6 μm.

*****

Tadatoshi Tanifuji, Tsuneo Horiguchi, and Masamitsu Tokuda

Baseband-frequency-response measurement of graded-index fibre using step-index fibre as an exciter

Electron. Lett. 15:203-204; 1979

For measuring reproducibility the baseband frequency response of a graded-index fibre, a mode exciter utilising an ordinary step-index multimode fibre has been proposed. The input mode power distribution and the frequency response of the fibre with the exciter are altered very little for axis offset. Input mode distribution excited indicates that excitation of nearly all modes takes place.

*****

G. Cancellieri

Time-dispersion measurement in optical fibre by near- and far-field scanning technique

Electron. Lett. 14:465-467; 1978

The time-dispersion measurement technique here reported, based on a differential mode-delay measurement, is a very simple one (only one modulation frequency is used); but, nevertheless, it has good features in accuracy and repeatability. It allows investigation of the mechanisms of fibre time dispersion and the effect of leaky rays.

*****

Leonard G. Cohen, Ivan P. Kaminow, Harry W. Astle, and Lawrence W. Stultz

Profile dispersion effects on transmission bandwidths in graded index optical fibers

IEEE J. Quantum Electron. QE-14:37-41; 1978

Transmission bandwidths of optical fibers would be maximized if their refractive index profiles were optimally graded. However, dispersive differences between fiber material constituents make the optimal power law profile exponent α depend on wavelength. This profile dispersion effect is significant for germanium borosilicate fibers and makes their observed transmission bandwidths change by more than 300 percent within a 650-1050 nm wavelength range.

Measurements are made in spectrally filtered white light from a xenon arc lamp that is sinusoidally modulated by an electrooptic crystal. Reduction of sine wave envelope intensity due to transmission in a fiber gives its baseband frequency response. The functional dependence of bandwidth on wavelength is used to diagnose whether α is larger or smaller than the optimal value which minimizes intermodal dispersion at particular wavelengths.

*****

Masahiro Ikeda and Henichi Kitayama

Transfer function of long spliced graded-index fibers with mode scramblers

Appl. Opt. 17:63-67; 1978

Transfer functions of long spliced graded-index fibers are determined with the steady state mode exciter and the mode scramblers loaded just after each splicing. Under these conditions, the total transfer function calculated by the linear combination of each fiber's transfer function is in good agreement with the measurement results. It has been found that the transmission bandwidth can be widened by using mode scramblers.

*****

D. B. Keck and R. Bouillie

Measurements on high-bandwidth optical waveguides

Opt. Commun. 25:43-48; 1978

Frequency response measurements on six high-bandwidth optical waveguides made by the doped deposited silica process are reported. One of these had an extrapolated bandwidth in excess of 3 GHz-km. From plane wave measurements the actual or optimum waveguide profile may be determined given the other. Data taken on a germanium borosilicate waveguide is in agreement with interference measurements.

*****

M. Maeda, K. Nagano, Y. Minai, and M. Tanaka

Baseband frequency response measurement system for optical components

Appl. Opt. 17:651-654; 1978

Knowledge of the baseband frequency responses of optical components is prerequisite to the design of optical fiber transmission systems. The sweep-frequency method is effective for obtaining frequency responses because of its large SNR. However, the use of GaAs lasers as optical signal sources involves several problems such as resonances below 1 GHz and spectrum broadening. In order to overcome these problems, a single transverse mode GaAs laser called a buried heterostructure GaAs laser was employed as an optical signal source in the sweep-frequency measurement system. This measurement system has a wideband flat sweep-frequency range of 0.5-1300 MHz as well as a wide dynamic range of more than 60 dB at optical levels.

*****

L. Martin, A. Cozannet, and C. Boisrobert

Amplitude and group delay distortion measurement in optical fibers--new technique using a link analyzer

Trans. IECE Japan E61:219-222; 1978

In this paper we report on amplitude and group delay distortion in optical fibres. Theoretical results are derived from the ray optics calculations. We show how we modified our frequency domain equipment previously designed for amplitude and phase vs frequency recording: experimental datas on step index fibres are given in 5-45 MHz frequency range. Final broadband remote operation system is discussed.

*****

Tadatoshi Tanifuji and Masahiro Ideda

Simple method for measuring material dispersion in optical fibres

Electron. Lett. 14:367-369; 1978

A simple and accurate method, using a sinusoidally modulated l.e.d., is proposed to measure material dispersion of optical fibres. By this method, material dispersion was measured using a step and a graded index fibre. The results were in good agreement with those of other methods.

*****

L. G. Cohen, H. W. Astle, and I. P. Kaminow

Frequency domain measurements of dispersion in multimode optical fibers

Appl. Phys. Lett. 30:17-19; 1977

A newly developed technique for directly measuring fiber dispersion in the frequency domain as a function of wavelength is described. A number of germanium- and boron-doped fibers have been examined. The least dispersive borosilicate graded-index fiber has a 1-dB bandwidth of 1 GHz, after 1.06 km of propagation at λ = 908 nm. Frequency domain measurements were inverted into the time domain after assuming that the phase of a power transfer function could be calculated from its amplitude spectrum.

*****

L. G. Cohen, H. W. Astle, and I. P. Kaminow

Frequency domain measurements of dispersion in multimode optical fibers

Tech. Digest, Opt. Fiber Trans. II, Williamsburg, TuE3-1--TuE3-4; 1977, Opt. Soc. Am.

*****

Itutaro Kobayashi, Masaki Koyama, and Kohichi Aoyama

Measurement of optical fiber transfer functions by swept-frequency technique and discussion of fiber characteristics

Electron. Commun. Japan 60-C:126-133; 1977

A new technique based on sweeping of the baseband frequency is proposed for determination of the frequency characteristics of step index fibers. First the principle, advantages and measurement setup are presented and then the baseband frequency characteristics and their dependence on distance are discussed in detail. The frequency characteristics show marked dependence on shape and variation in fibers with lengths from short to medium range and much new information is obtained. The hitherto unsettled problem of "L or √L" concerning the distance dependence of the fiber characteristics is also investigated. The relationship between bandwidth and loss is studied and a quantitative separation of loss into "selective" and "basic" components is achieved. Finally, the fluctuations of fiber characteristics and the main features of fiber transmission systems are briefly discussed and problems to be solved in the future are clarified. The present technique of baseband frequency sweep seems owing to its high frequency resolution, high SNR and high accuracy, which are sufficient for practical purposes.

*****

Shigeyuki Seikai, Masamitsu Tokuda, Koji Yoshida, and Naoya Uchida

Baseband frequency response of multimode step-index fibers measured using a new type of mode scrambler

Tech. Digest, IOOC-77, Tokyo, 411-414; 1977

For measuring frequency response of optical fiber, a mode scrambler utilizing sinusoidal bend and a new setup based on the attenuation comparison method have been proposed. Measurements for multimode step-index fibers have revealed that long fiber response can be anticipated from short fiber response by an appropriate choice of scrambler parameters.

*****

Paolo Spano

Chromatic delay in light emitting diodes, measurements and theory

Proc., Third Eur. Conf. Opt. Commun., Munich, 151-153; 1977

As already observed, the driving of LED at radio frequency causes the different parts of the optical spectrum to be differently dephased among themselves as if they were emitted at different times. Several measurements of the phenomenon are presented together with a possible interpretation.

*****

Masamitsu Tokuda, Shigeyuki Seikai, Koji Yoshida, and Naoya Uchida

Measurement of baseband frequency response of multimode fibre by using a new type of mode scrambler

Electron. Lett. 13:146-147; 1977

For measuring the frequency response of an optical fibre, a mode scrambler utilising a sinusoidal bend and a new set-up based on the attenuation-comparison method have been proposed. Measurements for multimode step-index fibres have revealed that the long-fibre response can be closely predicted from the short-fibre response, using an appropriate choice for the scrambler parameter.

*****

K. Yoshida, S. Seiki, M. Tokuda, and N. Uchida

Baseband frequency response of multimode step-index fibers measured using a new type of mode scrambler

Electron. Commun. Lab. Tech. J. (Japan) 26:2601-2611; 1977

For measuring frequency response of multimode step-index fibers, a mode scrambler utilizing sinusoidal bend and a new setup based on the attenuation comparison method have been proposed. The mode scrambler can control input mode power distribution with good reproducibility. Double beam method is used in the setup for nondestructive measurement of the frequency response with high accuracy.

*****

C. Y. Boisrobert, A. Cozannet, and C. Vassalo

Swept frequency transfer function measurement applied to optical fiber

IEEE Trans. Instrum. Meas. IM-25:294-297; 1976

Up to now, most of the experimental work on propagation through optical fibers was done using pulse measurements techniques. Short-light-pulse sources almost monochromatic and easy to drive to high-peak-power pulses are available on the optoelectronic components market; this is one of the main reasons why fiber manufacturers characterize their fibers by the broadening of the transmitted light pulse. This parameter does not provide enough information on the fiber behavior to the digital transmission system experts, unless one assumes a very-stable pulse shape at the fiber input and uses fast Fourier transform computation on time-domain signals.

This paper presents the more classical technique which is being used on transmission cables and devices. The central unit is the network analyzer which can simultaneously provide attenuation versus frequency and phase rotation versus frequency of any optoelectronic device coupled between the reference and the test inputs. Various light sources have been selected for their sinusoidal modulation facilities; most of our measurements were made with fast-light-emitting diodes (GaAlAs 0.82 μm) and some of them with a CW injection laser (GaAlAs 0.82 μm).

*****

R. Bouillie, J. C. Bizeul, and M. Guibert

Dependence over 7 kilometers of the transfer function of graded index fibres

Digest, Second Eur. Conf. Opt. Fibre Commun., Paris, 135-142; 1976

In this paper we discuss measurements and results performed on the transfer function of graded index fibres. The principle and the set-up are at first described. Then material dispersion, quality of the index profile and mode conversion are taken into account. A law is established which gives the transfer function of spliced fibres. This law is experimentally verified up to 8 kilometers.

From these results we draw some conclusions on the performances of these fibres for high bit rate systems.

*****

L. G. Cohen, H. W. Astle, and I. P. Kaminow

Wavelength dependence of frequency-response measurements in multimode optical fibers

Bell Sys. Tech. J. 55:1509; 1976

A newly developed technique for directly measuring fiber dispersion in the frequency domain as a function of wavelength is described. Spectrally filtered white light from a xenon arc lamp is sinusoidally modulated in the range 0 to 1 GHz by an electrooptic modulator and injected into a fiber. The procedure is to vary the modulation frequency and measure the corresponding sideband output power with a photomultiplier and spectrum analyzer. Ratio measurements between the test fiber and a short reference fiber give the baseband frequency response. A number of germanium- and boron-doped fibers have been examined. The least dispersive borosilicate graded-index fiber has a 1 dB bandwidth of 1 GHz, after 1.07 km of propagation at λ = 908 nm. The width broadens gradually with increasing wavelengths up to λ = 1100 nm.

*****

R. Auffret, C. Boisrobert, and A. Cozannet

Wobulation technique applied to optical fibre transfer function measurement

Proc., First Eur. Conf. Opt. Fibre. Commun., London, 60-61; 1975, IEE

*****

D. Gloge, E. L. Chinnock, and D. H. Ring

Direct measurement of the (baseband) frequency response of multimode fibers

Appl. Opt. 11:1534-1538; 1972

Incoherent light, transmitted via multimode fibers, represents a potential carrier for information that is directly modulated on the light envelope. The amplitude and phase characteristics of the envelope (baseband) signal are affected by the fiber waveguide because of group delay differences among the modes. We report on a technique that determines the baseband frequency response of the fiber system by comparing the beat spectra of light from a free-running laser before and after transmission through the fiber. As an example, we describe the measurement of 30 m of cladded multimode fiber. The 3-dB bandwidth was 700 MHz, somewhat larger than predicted on the basis of the computed group velocity differences.

3.4 Other Methods

W. D. Bomberger and J. J. Burke

Interferometric techique for the determination of dispersion in a short length of single mode optical fiber

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 101-104; 1980, U.S. Govt. Printing Office

*****

J. Piasecki, B. Colombeau, M. Vampouille, C. Froehly, and J. A. Arnaud

Nouvelle methode de mesure de la reponse impulsionnelle des fibres optiques (New method of measuring the impulse response of optical fibers)

App. Opt. 19:3749-3755; 1980

A new technique for measuring the temporal transfer function of optical fibers is described. The method consists of placing the fiber under test in one arm of a Mach-Zehnder interferometer excited by a broadband source. The temporal impulse response is obtained from a holographic reconstruction. The method requires only short lengths of single-mode or multimode fibers (less than 1 m). We have measured a dispersion of 0.3 nsec/km.nm at 0.59 µm with a single-mode fiber, in good agreement with theory. The arrival times of the various modes of multimode fibers are resolved.

*****

K. Daikoku and A. Sugimura

Direct measurement of wavelength dispersion in optical fibres--difference method

Electron. Lett. 14:149-151; 1978

A new method is described for direct and precise measurement of wavelength dispersion in the core of an optical fibre over a wide wavelength region.

*****

F. M. E. Sladen, D. N. Payne, and M. J. Adams

Measurement of profile dispersion in optical fibres: a direct technique

Electron. Lett. 13:212-213; 1977

A new technique allows direct determination of the wavelength-dipersive material properties of glasses within the fibre. Results obtained over a wide wavelength range are reported for both borosilicate and fluorine-doped cladding materials. The latter exhibits low profile dispersion.

*****

F. M. E. Sladen, D. N. Payne, and M. J. Adams

A method for the direct measurement of the inhomogeneous dispersion parameter in optical fibres

Tech. Digest, Opt. Fiber Trans. II, Williamsburg, TuE2-1--TuE2-4; 1977, Opt. Soc. Am.

*****

B. Crosignani, B. Daino, P. DiPorto

Coherence properties of electromagnetic fields propagating in multimode waveguides and application to the measurement of dispersion

Digest, Second Eur. Conf. Opt. Fibre Commun., Paris, 115-121; 1976

We present two methods which allow to measure mutual modal delays of the order of few picoseconds in optical fibers. Both methods are based on the observation of interference effects between different modes, which depend on the coherence properties of the exciting source and on the dispersion properties of the employed fiber. We present some results obtained by using a continuously tunable dye-laser as exciting source.

4.1 General

D. Marcuse and H. M. Presby

Index profile measurements of fibers and their evaluation

Proc. IEEE 68:666-688; 1980

The refractive index distribution in the core of a multimode optical-fiber waveguide plays an important role in determining the transmission properties of the guide. The closer the index profile is to the required ideal distribution, the greater the resulting information carrying capacity of the fiber. This review paper discusses methods for measuring the refractive index distribution in optical fibers and for predicting their impulse response and signal bandwidth from the measured profiles. Some attention is also given to preform and single-mode fiber profiling.

*****

H. M. Presby and D. Marcuse

Profile characterization of optical fibers and preforms

Tech. Digest, Symp. Optical Fiber Meas.-1980, Boulder, 31-36; 1980, U.S. Govt. Printing Office

*****

Herman M. Presby and Dietrich Marcuse

The index-profile characterization of fiber preforms and drawn fibers

Proc. IEEE 68:1198-1203; 1980

The information carrying capacity of multimode optical fibers is mainly determined by the quality of the refractive index distribution of their cores which, in turn, is determined by the distribution existing in the fiber's parent--the preform. This paper reviews methods that can be used to measure the index profiles of preforms--both multimode and single mode. Attention is also given to the effects of profile perturbations and means of eliminating them, as well as to applications of the techniques to fiber profiling.

*****

A. E. Karbowiak and D. H. Irving

Modelling optical fibers with arbitrary refractive-index profiles

Opt. Quantum Electron. 11:507-516; 1979

The characteristics of various models of refractive-index profile are examined. Four models are considered: (1) power-law profile, (2) truncated even polynomial profile, (3) truncated all-term polynomial profile, (4) Gauss-Chebychev approximation. The characteristics of the various models are examined with particular reference to the ray-delay times and the shape of the impulse response. The results show that models (1) and (2) are limited in their usefulness in representing practical profiles, while the approximation (4) is easily applied to a variety of practical profiles.

*****

H. M. Presby and D. Marcuse

Preform index profiling

Tech. Digest, Opt. Fiber Commun., Washington, 52-53; 1979, Opt. Soc. Am.

*****

Herman M. Presby, Dietrich Marcuse, and William G. French

Refractive-index profiling of single-mode optical fibers and preforms

Appl. Opt. 18:4006-4011; 1979

The application of the focusing method to measure the refractive-index profiles of single-mode optical fibers and preforms is described. In this automatic and nondestructive technique, the fiber or preform is immersed in index-matching oil, and collimated light is passed transversely through it. The intensity distribution of the transmitted light is detected with a video camera and processed with the aid of a computer-controlled video analysis system that provides the profile within a few minutes. The profiles of boron-doped and germanium-doped fibers and preforms with maximum Δn varying from 0.006 to 0.012 were measured with a repeatability of better than 1% and with a resolution better than 1 μm. The profiles of the preforms are in good agreement with those of the fibers and also with those of slab samples taken from the tips of the same preforms.

*****

J. P. Hazan, J. P. Cabanie, and J. J. Bernard

Method of assessing index profile data

Electron. Lett. 14:416-418; 1978

We describe a practical method for assessing profile data which is applicable to a large class of profiles. It is repeatable, can be used routinely with little computational hardware and visualises clearly and quantitatively the local α value along a radius.

*****

H. M. Presby, D. Marcuse, and L. M. Boggs

Rapid and accurate automatic index profiling of optical fibers

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 162-170; 1978, IEE

An automatic computer controlled video-analysis system has been developed to measure the refractive index profiles of optical fibers based on interference microscopy. Its use in determining the profiles for two distinct arrangements is discussed. In one, samples of the fiber are prepared for observations by cutting and polishing them into very thin slabs; in the second, the fiber is observed directly requiring no sample preparation at all, other than index-matching the cladding. Repeatabilities of the resulting profile measurements are within ±5 parts in 10^{-5} for the slabs and about ±3 parts in 10^{-4} for the whole-fiber samples.

*****

T. Okoshi

Optimum profile design of optical fibers and related requirements for profile measurement and control

Tech. Digest, IOOC-77, Tokyo, 391-394; 1977

This review paper first describes various approaches to the optimum design of refractive-index profiles of multimode and single-mode fibers. In the latter half, requirements for profile measurement and control are discussed; it is concluded that the present technologies are far from satisfactory to realize the really optimum profiles.

*****

P. V. H. Sabine

Refractive index profile determination in optical waveguides

A.T.R. Aust. Telecommun. Rev. 11:3-13; 1977

An adequate characterisation of optical fibres, and of waveguides for integrated optical circuits, demands a precise quantitative description of the refractive index variation over a cross-section of the particular component. The first part of this paper review available techniques for measuring this refractive index profile (RIP). The second part of this paper presents practical results for RIP measurements in stress-induced channel optical waveguides.

*****

B. Costa and B. Sordo

Measurements of the refractive index profile in optical fibres: Comparison between different techniques

Digest, Second Eur. Conf. Opt. Fibre Commun., Paris, 81-86; 1976

In this work we analyze two well known techniques for the measurement of the refractive index profile of optical fibres: they are the "near-field" technique and the reflection technique.

As regards the near field method we have calculated a correction factor that takes accurately into account the effects of leaky skew rays in step index fibres. For what concerns the reflection method we have introduced an experimental improvement that consists in immerging the fibre in a suitable liquid, so greatly enhancing the sensitivity of the measurement. Finally we have used both methods on the same samples of optical fibres and compared the results which resulted in good agreement.

*****

C. A. Burrus and R. D. Standley

Viewing refractive-index profiles and small-scale inhomogeneities in glass optical fibers: Some techniques

Appl. Opt. 13:2365-2369; 1974

Methods which have proved to be useful for measuring core-cladding refractive-index differences, for approximating refractive-index profiles, and for viewing various inhomogeneities in solid multimode optical fibers are described. Optical, transmission-interference, and scanning-electron-beam microscopy have been used, and the illustrations include examples of photomicrographs made by each of these techniques.

4.2 Interferometric Methods (Longitudinal)

I. D. Aggarwal, D. C. Leiner, and J. J. McAlarney

Refractive index modulation in optical fibers fabricated by the vapor oxidation process

In "Fiber Optics, Advances in Research and Development," Bernard Bendow and Shashanka S. Mitra, eds., Plenum Press; 1979

*****

Masao Hoshikawa, Shuzo Suzuki, Naoki Yoshioka, and Gotaro Tanaka

Simple method of refractive-index profile measurement: Q-fiber method

Trans. IECE Japan E61:217-219; 1978

This method can reduce the measuring time considerably and can improve spatial resolution by using a Q(quasi)-fiber, in comparison with an usual fiber-polishing method.

The overall measuring error was less than ±0.03% for the case of index difference ∓1%.

*****

Dennis C. Leiner

Measuring fiber index profile

Opt. Spect. 12:32-34; 1978

*****

H. M. Presby and H. W. Astle

Optical fiber index profiling by video analysis of interference fringes

Rev. Sci. Instrum. 49:339-344; 1978

An electronic technique to make fringe displacement measurements on the output field of an interference microscope to 1/1000 of a fringe, not including systematic errors, is described. The method, based upon line-selected video signal analysis, is applied to the evaluation of the refractive index profile of a graded index optical fiber. The index difference at a given point between the core and cladding is determined to better than 1 part in 10^5, implying a precision in the profile parameter α of ±0.005, an order of magnitude better than existing techniques.

*****

H. M. Presby, D. Marcuse, and H. W. Astle

Automatic refractive-index profiling of optical fibers

Appl. Opt. 17:2209-2214; 1978

A video-based system, which analyzes the output field of an interference microscope directly, has been developed to measure automatically the refractive-index distribution of optical fibers. Selected regions of the fringe field, detected with a silicon-vidicon, are digitized to 8-bit accuracy by an addressable video digitizer controlled with a programmable calculator. The calculator also makes fringe displacement measurements, corrects for certain misalignments, computes and plots the profile, and determines a best-fit power-law (α) curve. Profiles, with relative Δn measured accurate to a few parts in 10^5, obtained at different wavelengths and for different fiber orientations are presented.

*****

J. Stone and H. E. Earl

Optical fiber refractometry by interference microscopy: A simplified method

Appl. Opt. 17:3647-3652; (1978)

Index of refraction profiles of optical fibers are obtained by a new interference technique closely related to Mach-Zehnder microscope interferometry. Data are obtained from specially prepared samples using a conventional reflected light microscope. Excellent agreement is obtained with the results using the Mach-Zender method but at a considerable reduction in the cost and complexity of instrumentation.

*****

A. Nicia

Interference patterns from very thick samples for determining the profile of graded-index fibres

Electron. Lett. 13:309-310; 1977

Recent studies have pointed out the need for very thin (10 μm) fibre samples prepared for interferometric analysis of the refractive index profile of an optical fibre. We show that this is not necessary for all graded-index fibres with reasonable dispersion properties. Sample thicknesses of 125 μm, or more, can be used for fibres with a core diameter of about 50 μm.

*****

H. M. Presby and I. P. Kaminow

Binary silica optical fibers: Refractive index and profile dispersion measurements

Appl. Opt. 15:3029-3036; 1976

The variation of the core-cladding refractive index difference $\Delta nf(\lambda)$ is determined as a function of wavelength for GeO_2-SiO_2, TiO_2-SiO_2, P_2O_5-SiO_2, Al_2O_3-SiO_2, and Cs_2O-SiO_2 optical fibers. The measurements are obtained by electronically processing the output of an interference microscope illuminated by a monochromatic light source variable over the 0.5-1.1-μm range. The $\Delta nf(\lambda)$ results are utilized to calculate the precise grading of the refractive index profile characterized by an exponent $\alpha(\lambda)$ required to achieve a minimum modal dispersion. The material dispersion for these compositions is also calculated with the aid of available $n(\lambda)$ data for SiO_2.

*****

H. M. Presby, W. Mammel, and R. M. Derosier

Refractive index profiling of graded index optical fibers

Rev. Sci. Instrum. 47:348-352; 1976

Details of a method of determining the refractive index distribution of graded-index optical fibers based on interference microscopy are discussed. Sample preparation techniques, observational methods, and data reduction and analysis by a computer fitting program are described. Representative data for optical fibers prepared by chemical vapor deposition are shown.

*****

J. Stone and R. M. Derosier

Elimination of errors due to sample polishing in refractive index profile measurements by interferometry

Rev. Sci. Instrum. 47:885-887; 1976

The surface contouring caused by routine polishing of fibers and preforms in preparation for measurement of the refractive index profile has been studied. By observation of the surface interference fringes the effect of polishing on doped preforms is visualized. It is found that composition-dependent thickness variations occur which can cause a sizable error in the refractive index variation deduced by interference measurements in preforms (several percent) and in fibers (~50%). The difficulty is eliminated by several minutes of additional polishing on a hard lap.

*****

B. C. Wonsiewicz, W. G. French, P. D. Lazay, and J. R. Simpson

Automatic analysis of interferograms: Optical waveguide refractive index profiles

Appl. Opt. 15:1048-1052; 1976

Compensation of mode velocities in optical waveguides can be achieved by fabricating fibers having graded refractive index cores. One technique for measuring these index profiles is interference microscopy. We have developed a machine aided method for analysis of interference micrographs for the rapid determination of optical waveguide refractive index profiles. Our method consists of digitizing the interference micrograph with a scanning microdensitometer, followed by computer determination of the position of the center line of each fringe. The data obtained are then converted into refractive index and fiber radius information, which is used to calculate a best fit power law function.

*****

D. Gloge, I. P. Kaminow, and H. M. Presby

Profile dispersion in multimode fibres: Measurement and analysis

Electron. Lett. 11:469-471; 1975

An electronically scanned interference microscope has been used to measure the refractive-index profile and its dispersion in optical fibres. From these measurements, we find that the power-law profile that best equalises modal delays in GeO_2-SiO_2 fibres should have an exponent that varies between 1.9 and 2.5 in the wavelength range from 0.5 to 1.1 μm and is close to 2 at 0.9 μm.

*****

P. D. Lazay, J. R. Simpson, W. G. French, and B. C. Wonsiewicz

Interference microscopy: Automatic analysis of optical fiber refractive index profiles

Proc., First Eur. Conf. Opt. Fibre Commun., London, 40-42; 1975, IEE

*****

J. Stone and C. A. Burrus

Focusing effects in interferometric analysis of graded-index optical fibers

Appl. Opt. 14:151-155; 1975

The effects of ray bending due to graded refractive-index profiles have been studied in relation to the measurement of optical-fiber refractive-index profiles by microscopic interferometric techniques. In particular, the wavefront curvature produced by a simple parabolic profile has been calculated analytically. It is concluded that profile measurements by currently used methods require samples for which the fiber thickness (length) is much less than the effective focal length of the fiber. For parabolic profile fibers with diameter $d \gtrsim 100$ μm, this poses no problem; however, for small-core versions of this fiber, sample thicknesses of 10-15 μm may be required and an alternate measurement technique is described. Interferograms made on a Leitz transmitted-light interference microscope are included in illustrations.

*****

W. E. Martin

Refractive index profile measurements of diffused optical waveguides

Appl. Opt. 13:2112-2116; 1974

Refractive index profiles resulting from the fabrication of optical waveguides by diffusion techniques are measured using a reflection interferometric technique. In Cd-diffused ZnSe waveguides, the index variations are found to be complementary error functions that closely follow the composition changes for deep (>5 μm) diffusions. Shallow (<5 μm) diffusions produce waveguides in which the index profile is a complementary error function that differs significantly from the composition profile. The relationship between composition and refractive index is determined for Cd compositions less than 10%. Refractive index profiles in commercially available diffused glass waveguides (SELFOC rod and fibers) are also described.

*****

Eric G. Rawson and Richard G. Murray

Interferometric measurement of SELFOC dielectric constant coefficients to sixth order

IEEE J. Quantum Electron. QE-9:1114-1118; 1973

A simple and sensitive interferometric technique which yields accurate measurements of the 2nd-, 4th-, and 6th-order coefficients of the series expansion for the radial distribution of the dielectric consstant of SELFOC or other GRIN rods is reported. Such data are required, for example, in predicting temporal dispersion in SELFOC fiber waveguides. The interferometer directly measures the relative phase delay along meridional-ray paths of different initial field angles. The mathematical analysis consists of finding the 2nd-, 4th-, and 6th-order coefficients which yield the best least squares fit to the measured phase shifts. The 4th-order results are found to be in good agreement with those of I. Kitano and co-workers. As an experimental application we describe a small, mechanically stable, diffraction-limited collimator for use with an optical fiber waveguide.

4.3 Interferometric Methods (Transverse)

Yasuo Kokubun and Kenichi Iga

Refractive-index profile measurement of preform rods by a transverse differential interferogram

Appl. Opt. 19:846-851; 1980

A nondestructive refractive-index profile measurement of optical-fiber preform rods by means of a transverse-differential-interference method is given. The error resulting from the data reading of a fringe center is investigated by computer simulation and is confirmed to be less than about 1% of the index differenc between the core and the cladding. The refractive-index profile of a preform rod was measured, and it almost coincided with that of the fiber drawn from the rod. The elliptic deformation of the core and its variation along the longitudinal axis were measured.

*****

K. Iga, Y. Kokubun, and T. Omoto

Nondestructive measurement of refractive index profiles of optical fiber preform rods

IEEE J. Quantum Electron. QE-15:80D-81D; 1979

*****

H. M. Presby, D. Marcuse, H. W. Astle, and L. M. Boggs

Rapid automatic index profiling of whole-fiber samples: Part II

Bell Sys. Tech. J. 58:883-902; 1979

Automatic, nondestructive methods have been developed for measuring and analyzing the refractive index-matching oil and illuminated transversely to its axis in a single-pass interference microscope. The output field of the microscope is automatically processed with a video-digitized, computer-controlled system, and the profile is determined by the solution of an integral equation that can handle arbitrary variations in the index distribution. The resulting profiles are reproducible to approximately 1 percent and can be determined within a few minutes after fiber fabrication. Details of a rapid video scanning procedure and of error estimates involved in solving the integral equation are presented along with representative profiles.

*****

Kenichi Iga and Yasuo Kokubun

Formulas for calculating the refractive index profile of optical fibers from their transverse interference patterns

Appl. Opt. 17:1972-1974; 1978

A set of successive approximation formulas for calculating the refractive index profile of optical fibers from their transverse interference patterns has been derived. The probing ray refraction due to the index gradient in the core is corrected for by these formulas, and the accuracy of index determination is improved. The error is confirmed to be less than 3×10^{-3}% of the index difference by means of computer simulations. The index profiles of some optical fibers are practically determined with the help of these formulas.

*****

Y. Kokubun and K. Iga

Index profile measurement of optical fibers by means of a transverse interferogram--further considerations on its accuracy

Trans. IECE Japan E61:184-187; 1978

The accuracy of the formulas for calculating the refractive index profile from its transverse interference pattern is investigated in detail by computer simulations. The principle error is confirmed to be about 10^{-3}% of the index difference between the core and the cladding. The transverse interference patterns from a multimode graded index fiber and a thin fiber of which core diameter is several microns are obtained by using an interferometer microscope and their refractive index profiles were practically determined with the help of these formulas. Their α parameters were obtained.

*****

K. Iga and Y. Kokubun

Precise measurement of the refractive index profile of optical fibers by nondestructive interference method

Tech. Digest, IOOC-77, Tokyo, 403-406; 1977

The accuracy of the transverse interference method has been raised up by fully correcting a probing ray refraction due to the index gradient of the fiber. A simulation shows that the accuracy is in principle within 0.3 % of the index difference between the core center and the cladding. The index profiles of some fibers were practically measured and it was confirmed that this method can be used for a precise, nondestructive, and fast measurement.

*****

Yasuo Kokubun and Kenichi Iga

Precise measurement of the refractive index profile of optical fibers by nondestructive interference method

Trans. IECE Japan E60:702-707; 1977

In this paper, the accuracy of the transverse interference method has been raised up by fully correcting a probing ray refraction due to the index gradient of the fiber. A simulation shows that the accuracy is in principle within 0.3 % of the index difference between the core center and the cladding. The index profiles of some fibers were practically measured and it was confirmed that this method can be used for a precise, nondestructive, and fast measurement.

*****

Y. Maruyama, K. Iwata, and R. Nagata

Determination of axially symmetric refractive index distribution from directions of emerging rays

Appl. Opt. 16:2500-2501; 1977

A successful verification of a method for numerical reconstruction of axially symmetric refractive index distribution is reported. Directions of rays emerging from a test object are used as input data for reconstruction. They are obtained by numerically calculating the spatial frequency of the fringes in an interferogram. It is also shown that the same data can be obtained directly by counting moiré fringes arising from two slightly displaced interferograms. An acrylic resin immersed in liquid is used as a test object. The reconstruction is carried out with errors of a few percent.

*****

Yasuji Ohtsuka and Yutaka Shimizu

Radial distribution of the refractive index in light-focusing rods: Determination using Interphako interference microscopy

Appl. Opt. 16:1050-1053; 1977

An interferometric technique for the determination of the radial distribution of the refractive index in light focusing plastic rods (LFR) has been developed using the shearing method of Interphako interference microscopy. We have derived mathematical expressions for the shape of interference fringes across the rod assuming the index distribution of LFR is described by $n(r) = n_0(1-ar^2+br^4+cr^6+dr^8)$ in which a, b, c, and d are distribution constants. The distribution constants were determined using a least-squares technique on a computer from the actual shape of fringes. Results for the representative cases are shown.

*****

M. J. Saunders and W. B. Gardner

Nondestructive interferometric measurement of the delta and alpha of clad optical fibers

Appl. Opt. 16:2368-2371; 1977

It is shown that interferograms generated by passing light perpendicular to the axis of a fiber can be used to obtain the maximum refractive index difference and the index profile shape to better than ±10% accuracy in regions of the core where α is constant. This techique avoids the time consuming sample preparation required for the slab method, the propagation problems associated with the near-field technique, and the surface quality problem associated with the reflection technique.

*****

F. T. Stone

Rapid optical fiber delta measurement by refractive index tuning

Appl. Opt. 16:2738-2742; 1977

A technique is presented for rapidly measuring Δ of optical fibers with profiles closely approximating $n(r) = n(o)[1 - \Delta(r/a)^{\alpha}]$, the $\Delta \ll 1$ limit of the two-parameter Gloge-Marcatili profile. Error analysis indicates an accuracy of about ±9%. The method is as follows: Using a Michelson interferometer together with a microscope, the transverse optical path through the center of a fiber immersed in index matching fluid is set equal to the optical path through the fluid. This is accomplished by varying the temperature of the fluid. The value of Δ can then be determined from a knowledge of the refractive index of the fluid inferred from temperature measurements. Good agreement is shown between Δ values measured by this technique and those measured by two other interferometric techniques. The possible use of this method to determine α, or to determine the actual profile if it does not follow the assumed shape, is discussed.

*****

M. E. Marhic, P. S. Ho, and M. Epstein

Nondestructive refractive-index profile measurements of clad optical fibers

Appl. Phys. Lett. 26:574-575; 1976

An interferometric method in conjunction with Abel inversion is used to precisely measure the index of refraction profile of clad optical fibers without perturbing them. The sample is immersed in index-matching fluid, so that fiber index variations cause only small phase shifts for rays propagating perpendicular to the axis, making interferometric methods applicable.

4.4 Other Transverse Methods

P. L. Chu and D. Peri

Holographic measurement of refractive-index profile of optical fibre preform

Electron. Lett. 16:876-877; 1980

A holographic method of measuring the refractive-index profile of an optical fibre preform is presented. It uses the principle of shearing interferometry. The method is simple and allows measurements to be repeated even after the preform has been withdrawn for fibre drawing.

*****

T. Okoshi and M. Nishimura

Automated measurement of refractive index profile of VAD preforms by fringe-counting method

J. Opt. Commun. 1:18-21; 1980

A new method for measuring the refractive index profile of a preform rod produced by the VAD (Vapor-phase Axial Deposition) scheme is proposed. This method, called the fringe-counting method, features a relatively good accuracy and efficient data collection for such relatively "thick" samples as the preform.

An automated, computer-controlled measuring system has been developed and used in the experiment. Computer simulations shown that the developed system has an accuracy good enough for most practical purposes (below 0.2% in most cases).

*****

T. Okoshi, M. Nishimura, and M. Kosuge

Nondestructive measurement of axially nonsymmetric refractive-index distribution of optical fibre preforms

Electron. Lett. 16:722-724; 1980

A nondestructive computer-aided measurement of the arbitrary two-dimensional refractive index distribution of an optical fibre preform is described. The angle of refraction of rays in the preform is measured by an optical set-up which features the use of a triangular mask for converting the angle of rays to their displacement. The index distribution is computed from the information on these refraction angles.

*****

D. Peri and P. L. Chu

Index profile determination in transition region of optical fibre preform

Electron. Lett. 16:916-918; 1980

It is shown that the refractive-index profile in the transition region of an optical fibre preform can be obtained by a combination of a measurement of the deflection function and a ray-tracing procedure.

*****

I. Sasaki, D. N. Payne, and M. J. Adams

Measurement of refractive index profiles in optical-fibre preforms by spatial-filtering technique

Electron. Lett. 16:219-221; 1980

A nondestructive technique based on spatial filtering is presented for measuring the refractive-index profile in an optical-fibre preform. The method is simple, accurate and has sufficient resolution to enable detailed profiles of single-mode preforms to be obtained.

*****

C. Seakeang, P. L. Chu, and T. W. Whitbread

Nondestructive measurement of refractive-index profile and cross-sectional geometry of optical fiber preforms

Appl. Opt. 19:2025-2030; 1980

A modified focusing method for measuring simultaneously the refractive-index profile and the cross-sectional geometry of an optical fiber preform is presented. In this method the preform is immersed in index-matching liquid, and collimated light is made to impinge on the preform laterally. The intensity distributions of the transmitted light are detected on two planes inside the preform core. From the recorded light intensity distributions, the deflection function is calculated. After the preform has been rotated through 180° and the necessary data have been collected, a numerical inversion is performed to obtain the 2-D index profile. In this paper, the principle, the experimental setup, and results are described. The sensitivity of the method to measurement erors and the accuracy of the inversion formula were investigated by computer simulations. It was found that the error of the index profile measurement was <1%.

*****

L. M. Boggs, H. M. Presby, and D. Marcuse

Rapid automatic index profiling of whole-fiber samples: Part 1

Bell Sys. Tech. J. 58:867-882; 1979

A new interferometric method not requiring any sample preparation is presented for determining the refractive-index profiles of optical fibers. The whole fiber is immersed in index-matching oil and placed transversely under an interference microscope. The determination of the refractive index distribution for an arbitrary, circularly symmetric fiber core requires the solution of an integral equation. In this first of two papers on the subject, we describe a method which accomplished its solution by assuming that the fiber core consists of a large number of concentric circular cylinders of step-wise constant refractive index. The index distribution can then be obtained by determining the index values of each layer successively. The method has been applied to double- and single-pass interferometric arrangements which are being compared here. The single-pass method is reproducible to about 1 percent and provides the complete index distribution within minutes with the help of a computer-controlled video-analysis system. The results of this method are in excellent agreement with profiles obtained from polished slabs of the same fiber.

*****

P. L. Chu and C. Saekeang

Nondestructive determination of refractive-index profile and cross-sectional geometry of optical-fibre preform

Electron. Lett. 15:635-636; 1979

A nondestructive method is presented to determine simultaneously the refractive-index profile and the cross-sectional geometry of a preform. In this method, a plane wave is made to impinge on the preform laterally and the power distribution of the scattered pattern is recorded. From the recorded power, the ray pathlength difference is calculated. After the preform has been rotated through 360° and the necessary data collected, a numerical inversion is performed to obtain the index profile and cross-sectional geometry.

*****

P. L. Chu and T. Whitbread

Nondestructive determination of refractive index profile of an optical fiber: Fast Fourier transform method

Appl. Opt. 18:1117-1122; 1979

A nondestructive technique of determining the refractive index profile of an optical fiber is presented. This method involves collecting the pathlength data of rays passing through the fiber due to side-illumination and taking the fast Fourier transform of these data followed by a numerical integration. It is found that this technique yields results in good agreement with measurements from the near-field scanning technique. The advantage of the present method is that it can readily be extended to fibers of noncircular cross section.

*****

P. L. Chu and T. Whitbread

Measurement of refractive-index profile of optical fibre preforms

Electron. Lett. 15:295-296; 1979

An experimental system for nondestructive measurement of the refractive-index profile of an optical fibre preform is reported. The result shows that the profile does not significantly change from the preform stage to fibre stage.

*****

P. L. Chu

Nondesctructive refractive-index profile measurement of elliptical optical fibre or preform

Electron. Lett. 15:357-358; 1979

A nondestructive method of determining the refractive-index profile of an elliptic optical fibre or preform is reported. For the fibre, the pathlength data obtained from interference microscopic measurement are used. For the preform, the ray exit angles are used. These data are put into an integral that can be inverted numerically to obtain the reconstructed.

*****

D. Marcuse

Refractive index determination by the focusing method

Appl. Opt. 18:9-13; 1979

We show that it is possible to determine the refractive index distribution of a fiber or preform with slight index variation by observing the power distribution of the light field that is focused by the core acting as a lens. This method requires index matching of the cladding and illumination of the core at right angles to its axis with a broad beam of incoherent collimated light. The refractive index distribution is obtained after two numerical integrations to be performed by computer. The first integration establishes the relation between the output and input ray positions from the observed power distribution, the second uses this information to determine the refractive index distribution. However, it is not necessary to solve a large system of simultaneous equations. The sensitivity of the method to measurement inaccuracies was tested by computer simulation. It was found that the method has a built in smoothing effect that attenuates rather than amplifies measurement errors.

*****

D. Marcuse and H. M. Presby

Focusing method for nondestructive measurement of optical fiber index profiles

Appl. Opt. 18:14-22; 1979

A new method to determine the refractive-index distributions of the cores of optical fibers is presented. The fiber is immersed in index matching oil to eliminate light refraction at the outer core boundary. Collimated light is passed transversely through the fiber core and is detected with a microscope focused just above the plane of the core boundary. The intensity distribution in the image plane is recorded with the aid of a computer-controlled video-analysis system. The refractive-index profile of the fiber core is then computed from this intensity distribution. In this paper we present error estimates and show how well the focusing method agrees with the interferometric slab method. The repeatability of the index measurement is approximately 2%, an error which is easily attributable to incident light level fluctuations.

*****

H. M. Presby and D. Marcuse

Preform index profiling (PIP)

Appl. Opt. 18:671-677; 1979

An automatic and nondestructive focusing method to determine the refractive index distributions of optical fiber preforms is presented. The preform is immersed in index matching oil, and collimated light is passed transversely through it. The intensity distribution of the transmitted light is detected with a vidicon camera equipped with a low f-number lens focused just outside the core boundary. Recording and processing the light distribution follow the aid of a computer-controlled video-analysis system. The refractive index profile of the preform is computed from the intensity distribution, plotted, and fitted with a power-law curve within several minutes time. The repeatability of the index measurement is better than 1%, and excellent agreement is obtained with profiles determined interferometrically using slab samples from the tips of the same preforms.

*****

H. M. Presby and D. Marcuse

Optical fiber preform diagnostics

Appl. Opt. 18:23-30; 1979

A sensitive, nondestructive, and noncontacting method is described for obtaining structural information on the preforms from which optical fibers are produced. The technique allows the determination of the core size and the core eccentricity from direct observation of light traversing the preform normal to its axis. Also observable are the core-cladding interface structure, individual deposition layer structure and variations, imperfections within the core and the cladding, and the presence of an axial refractive-index depression. Results and implications from a variety of multimode and single-mode preforms are presented along with a theoretical analysis of the observations.

*****

Charoon Saekeang and Pak L. Chu

Nondestructive determination of refractive index profile of an optical fiber: Backward light scattering method

Appl. Opt. 18:1110-1116; 1979

A new nondestructive technique is presented for determining the refractive index profile of an optical fiber from its backscattered pattern arising from a normally incident laser beam to the fiber axis. The proposed method requires no sample preparation or index matching liquid. The principle of the method is to construct a deflection function from the measured pattern. The index profile can then be determined by the inversion of an Abel integral equation. Good agreement is obtained between the index profile determined by this technique and that measured by the near-field scanning technique.

*****

L. S. Watkins

Laser beam refraction traversely through a graded-index preform to determine refractive index ratio and gradient profile

Appl. Opt. 18:2214-2222; 1979

A technique is described which permits the determination of geometric and refractive index characters of graded-index preforms from measurements of the refraction of rays traced through the preform perpendicular to the preform axis. A computer program was developed to trace rays through graded-index preforms to display the refracting effect of the index properties and relate the ray incidence angle to its deflection in traversing the preform. An experimental apparatus has been developed in which a narrow beam of laser radiation is directed at the preform and its deflection angle measured. Comparison between the experimental results and the ray trace calculations using an interactive curve-fitting procedure gave nondestructive determinations of the refractive index ratio Δ and index gradient profile parameter α as well as measurement of the core dimensions.

*****

K. F. Barrell and C. Pask

Nondestructive index profile measurement of non-circular optical fibre preforms

Opt. Commun. 27:230-234; 1978

We present quantitative results for the effect of noncircularity on a method recently proposed by Chu for the measurement of the refractive index profile of an optical fibre preform. Analytical studies show how Chu's method can be applied to elliptical preforms.

*****

Ernst Brinkmeyer

Refractive-index profile determination of optical fibers by spatial filtering

Appl. Opt. 18:1117-1122; 1979

*****

Kazuo Hotate and Takanori Okoshi

Semiautomated measurement of refractive-index profiles of single-mode fibers by scattering-pattern method

Trans. IECE Japan E61:202-205; 1978

Semiautomated measurement of the refractive-index profiles of single-mode fibers using the scattering-pattern method developed by the same authors is described. The scattering-pattern method features very high resolution, typically 0.2 μm: hence at present it is the only method suitable for single-mode fibers. The measurements have been performed by using a semiautomated system. This system consists of an automated measuring apparatus of the scattering pattern of softwares for calculating the refractive-index profile. The obtained profiles are compared with those of preforms.

*****

A. Landraud

Tomographie transaxiale par voie optique: Application a la mesure d'indicie des fibres (Transaxial tomography by an optical method: Application to the measurement of fiber indices

Opt. Commun. 25:305-310; 1978

Usual transaxial tomography requires lengthy and computer performed calculations. It can be shown that a coherent double diffraction optical process gives good results without numerical treatment. The filter used is a so-called "ρ" filter; we describe a fully automatized technique for the realization of amplitude and phase filters. We present also here a new technique for coding information issuing from the scanning apparatus, which makes possible real time coding, thus avoiding image data storage. We describe an optical setup for the simulation of transaxial tomography together with a method for measuring three dimensional refractive index profiles (for instance in fibers). This process can also be fully automatized and performed in real time with incoherent illumination.

*****

C. Saekeang and P. L. Chu

Nondestructive determination of refractive-index profile of an optical fibre: Forward light scattering method

Electron. Lett. 14:802-804; 1978

A nondestructive technique is presented for determining the refractive-index profile of an optical fibre from its forward-scattered pattern arising from a normally incident laser beam. This method does not require any index-matching liquid and is not limited to single-mode fibres. It uses as essential information only the angular positions of the extrema in the measured pattern.

*****

Ernst Brinkmeyer

Refractive-index profile determination of optical fibers from the diffraction pattern

Appl. Opt. 16:2802-2803; 1977

*****

P. L. Chu

Nondestructive measurement of index profile of an optical-fibre preform

Electron. Lett. 13:736-738; 1977

A simple and fast nondestructive method of measuring the index profile of an optical-fibre preform is presented. In this method, a laser beam is shone perpendicularly to the preform axis, and the exit angle of its backscattered ray is recorded as a function of the distance of the incident ray from the horizontal axis. A numerical integration involving these exit angles gives the profile.

*****

K. Hotate and T. Okoshi

Semiautomated measurement of refractive-index profiles of single-mode fibers by scattering-pattern method

Tech. Digest, IOOC-77 Tokyo, 399-402; 1977

Semiautomated measurement of the index profiles of single-mode fibers using the scattering-pattern method developed by the same authors is described. The scattering-pattern method features very high resolution, typically 0.2 μm; hence at present it is the only method suitable for single-mode fibers. The obtained profiles are compared with those of preforms.

*****

T. Okoshi and K. Hotate

Refractive-index profile of an optical fiber: Its measurement by the scattering pattern method

Appl. Opt. 15:2756-2764; 1976

This paper describes a new method (the scattering-pattern method) for determining the refractive-index profile in an optical fiber from its scattering pattern for a normally incident laser beam. The proposed method is applicable to an arbitrary profile and is nondestructive. The spatial resolution is high, and the accuracy is good when the fiber diameter and the refractive-index variation are relatively small. The drawback is that a large number of data are required; however, this difficulty has been overcome by using the automated measuring system described in this paper. The profile obtained shows good agreement with design data.

*****

T. Okoshi and K. Hotate

Computation of the refractive index distribution in an optical fibre from its scattering pattern for a normally incident laser beam

Opt. Quantum Electron. 8:78-79; 1976

*****

D. Marcuse and H. M. Presby

Light scattering from optical fibers with arbitrary refractive-index distributions

J. Opt. Soc. Am. 65:367-375; 1975

A scattering theory is presented, which is capable of predicting the light-distribution pattern that arises when a clad optical fiber of arbitrary core refractive-index distribution is illuminated by a laser beam perpendicular to its axis. Theoretical predictions are compared to experimental results in the backscattering direction, with excellent agreement for fibers of practical interest leaving core and cladding diameters on the order to 50 and 150 μm, respectively. Considerable sensitivity to parameter variations has been observed and implications for diameter and refractive-index distribution determinations are discussed.

*****

Yung S. Liu

Direct measurement of the refractive indices for a small numerical aperture cladded fiber: A simple method

Appl. Opt. 13:1255-1256; 1974

*****

H. M. Presby and D. Marcuse

Refractive index and diameter determinations of step index optical fibers and preforms

Appl. Opt. 13:2882-2885; 1974

A new method to determine the index of refraction in combination with the diameter of the cores of step-index optical fibers and preforms is presented. The technique is based on an analysis of the backscattered light when a beam from a cw laser impinges transversely upon the fiber or preform. A geometrical-optics analysis shows that, under appropriate assumptions, a combination of the refractive indexes and the radii of the core and cladding can be determined from unique characteristics of the backscattered radiation pattern. The theory is compared to experimental observations with excellent agreement.

4.5 Near-Field Methods

K. F. Barrel and C. Pask

Leaky ray correction factors for elliptical multimode fibres

Electron. Lett. 16:329-330; 1980

Leaky ray attenuation in elliptical graded-index fibres is related to the changes in the ray parameter that are induced by fibre ellipticity. Parabolic index fibres are described in detail. Results are given for the correction factors which must be applied to the measured near-field intensity in order to obtain the refractive-index profile.

*****

M. Young

Calibration technique for refracted near-field scanning of optical fibers

Appl. Opt. 19:2479-2480; 1980

*****

M. Young

Linearity and resolution of refracted near-field scanning technique

Tech. Digest, Opt. Fiber Meas.-1980 Boulder, 37-40; 1980, U.S. Govt. Printing Office

*****

J. J. Ramskov-Hansen, M. J. Adams, A. Ankiewicz, and F. M. E. Sladen

Near-field correction factors for elliptical fibres

Electron. Lett. 16:580-581; 1980

Correction factors for use with the near-field scanning method of index profile determination of elliptical fibres are presented. Theory and experiment show that different correction factors are required for the major and minor axes.

*****

P. V. H. Sabine, F. Donaghy, and D. Irving

Fibre refractive-index profiling by modified near-field scanning

Electron. Lett. 16:882-883; 1980

A modified bounded-mode near-field scanning method for determining the refractive-index profiles of optical fibres is described. The technique is simple to implement and allows the fibre numerical aperture and geometry to be measured.

*****

B. Daino, S. Piazzola, and A. Sagnotti

Spatial coherence and index-profiling in optical fibers

Opt. Acta. 26:923-928; 1979

A simple relation is proved to exist between the coherence properties of the light emerging from the end cross-section of multi-mode optical fibres, excited by means of spatially incoherent sources, and their refractive index distributions. Experimental results showing the possibility of visualizing the index profile are reported.

*****

K. I. White

Practical application of the refracted near-field technique for the measurement of optical fibre refractive index profiles

Opt. Quant. Electron. 11:185-196; 1979

Both the theoretical basis and experimental realization of the refracted near-field technique for the direct measurement of optical fibre profiles are presented. The technique requires minimal sample preparation, no computation and is applicable to both single and multimode fibres. Both the core and the cladding are profiled. After outlining the problems associated with other techniques, the use of this method for the measurement of fibre profile, numerical aperture and geometry is discussed. Leaky mode rejection and resolution are treated in detail. A fitting procedure for determining the α-value of a profile is given. The experimental apparatus is fully discussed. Results are presented to illustrate both the applicability of the technique to single and multimode fibres and also the rejection of leaky modes. The experimental sensitivity is shown sufficient to reveal an index fluctuation having a wavelength <1 μm and an amplitude of <0.0001.

*****

B. Daino, S. Piazzola, and A. Sagnotti

A new method for measuring the index profile of optical fibers

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 156-161; 1978

We report a new non-destructive method for measuring the index profile of optical fibers.

By means of simple arguments we show that a direct relation exists between the absolute value of the complex degree of coherence of the transmitted light and the value of the refractive index in every point of the exit face of an optical fiber.

*****

K. I. White

The measurement of the refractive index of optical fibres by the refracted near field technique

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 146-155; 1978

The refracted near field technique gives a direct measurement of an optical fibre profile without any need for computation or correction. Sample preparation is simple and end degradation is not a problem. Leaky modes make no contribution. The method is applicable to both multimode and monomode fibres and, as well as the profile, yields the numerical aperture of the fibre together with the core and clad diameters, core centrality and ellipticity. It thus avoids the drawbacks associated with other techniques while giving more information. This paper discusses in detail both the theory of the method and also practical aspects of the experiment. Typical results are presented for both multimode and monomode fibres.

*****

M. J. Adams, D. N. Payne, F. M. E. Sladen, and A. Hartog

Resolution limit of the near-field scanning technique

Proc., Third Eur. Conf. Opt. Commun., Munich, 25-27; 1977

The near-field intensity distribution in a fully-excited fibre is calculated by superposition of propagating modes. It is shown that the resolution of the near-field scanning technique is limited by the number of modes supported by the fibre. Experimental confirmation is given.

*****

M. Eve

Near field and far field power distributions in a multimode graded fibre

Opt. Quant. Electron. 9, 459-464; 1977

It is shown in this paper that the near field and far field power distributions corresponding to any distribution of rays in an arbitrary graded fibre, reach a steady state along the fibre. This steady state is usually a function of the input distribution of rays and of the refractive index profile of the fibre. The case of parallel beam injection is considered and an analytical expression for the near field power distributions for any arbitrary profile is found. This suggests a new method of refractive index profile measurement which is free of leaky ray corrections and can be very sensitive near the optimum profile for time dispersion.

*****

K. Petermann

Uncertainties of the leaky mode correction for near-square-law optical fibres

Electron. Lett. 13:513-514; 1977

It is shown that the leaky-mode correction as used, for example, for the near-field scanning technique, becomes uncertain for near-square-law fibres if they deviate from perfect circular symmetry. Results for the transition of the leaky-mode behaviour are presented.

*****

W. J. Stewart

A new technique for measuring the refractive index profiles of graded optical fibres

Tech. Digest, IOOC-77:395-398; 1977

A new near-field technique has been devised that offers substantially better performance than existing methods. In particular no leaky mode correction is necessary, detail resolution is improved and both core and cladding are profiled, enabling the absolute indices to be determined.

*****

G. T. Summer

A new technique for refractive profile measurement in multimode optical fibres

Opt. Quantum Electron. 9:79-82; 1977

*****

M. J. Adams, D. N. Payne, and F. M. E. Sladen

Length-dependent effects due to leaky modes on multimode graded-index optical fibres

Opt. Commun. 17:204-209; 1976

The radiation losses of tunnelling leaky modes in graded-index optical fibres are calculated theoretically, and it is shown that the near-field intensity profile has a length dependence. Consequently measurements of the near-field intensity distribution do not give the refractive index profile directly, and a correction factor must be applied. We have investigated this factor and find that it depends only on a single normalisation involving fibre length, core radius and normalised frequency. A further use of the correction factor is to determine the total power attenuation due to the loss of leaky modes.

*****

M. J. Adams, D. N. Payne, and F. M. E. Sladen

Correction factors for the determination of optical-fibre refractive index profiles by the near-field scanning technique

Electron. Lett. 12:281-283; 1976

Numerical calculations are presented of the correction factor for use with the near-field scanning method of index profile determination. It is shown that a single curve can be applied to a range of possible profiles, and a numerically obtained average curve is given.

*****

J. A. Arnaud and R. M. Derosier

Novel technique for measuring the index profile of optical fibers

Bell Sys. Tech. J. 55:1489-1508; 1976

A novel technique for measuring the refractive index profile of optical fibers is demonstrated, which offers substantial advantages over alternative methods. The method consists of illuminating a small area of the fiber core and measuring the total transmitted power. The transmission of leaky modes is accounted for in the manner reported previously by other authors. The index profiles of germanium-doped fibers obtained by this technique are compared to interferometric measurements. The resolution is shown to be limited by wave optics effects to about $\lambda_0(4n\sqrt{2\Delta})^{-1}$, where $\Delta \equiv \Delta n/n$. The distortion of the index profile as the wavelength varies and wave-optics effects are investigated.

*****

Robert Olshansky

Leaky modes in graded index optical fibers

Appl. Opt. 15:2773-2777; 1976

Leaky mode attenuation coefficients for graded index optical fibers are derived using the WKB approximation. For the case of a parabolic index profile, the attenuation coefficients for explicitly evaluated and used to calculate the leaky mode contribution to near field and attenuation measurements. Failure to observe the expected leaky mode contributions in several graded index fibers is interpreted as evidence for the presence of an additional loss mechanism.

*****

F. M. E. Sladen, D. N. Payne, and M. J. Adams

Determination of optical fiber refractive index profiles by a near-field scanning technique

Appl. Phys. Lett. 28:255-258; 1976

A simple and rapid method is described for determining the refractive index profile of an optical fiber by observation of the near-field intensity distribution. It is shown that in many cases the presence of tunnelling leaky modes is unavoidable and that these cause a length-dependent error in the measurement. A correction factor is developed which may be applied to the measured intensity profile once the fiber length, core diameter, and numerical aperture are known. Examples are given of measurements made on both step and graded-index fibers.

*****

D. N. Payne, F. M. E. Sladen, and M. J. Adams

Index profile determination in graded index fibres

Proc., First Eur. Conf. Opt. Commun., London, 43-45; 1975, IEE

4.6 Reflection Methods (Longitudinal)

T. Wilson, J. N. Gannaway, and C. J. R. Sheppard

Optical fibre profiling using a scanning optical microscope

Opt. Quantum Electron. 12:341-345; 1980

A scanning optical microscope is used to measure directly the refractive-index profile of an optical fibre. The effects of illuminating the fibre end with a highly convergent beam of light are considered.

*****

J. Stone and H. E. Earl

Surface effects and reflection refractometry of optical fibres

Opt. Quantum Electron. 8:459-463; 1976

Refractive index profiles of several types of silica-based low-loss optical fibres have been measured by the surface reflection technique. When polished samples are used inaccurate data are obtained. For germanium- and phosphorous-doped samples good results are obtained using samples prepared by fracturing the end of the fibre. For borosilicate fibres rapid changes due to atmospheric exposure result in inaccurate data.

*****

W. Eickhoff and E. Weidel

Measuring method for the refractive index profile of optical glass fibres

Opt. Quantum Electron. 7:109-113; 1975

A new method for measuring the refractive index profile of optical glass fibres is described. This simply monitors the reflection of a focused laser beam from a polished fibre end face. Detailed tests on the accuracy and resolution of the method are described and the index profiles of several fibres are given as an example of its feasibility.

*****

Masahiro Ikeda, Mitsuhiro Takeda, and Haruo Yoshikiyo

Refractive index profile of a graded index fiber: Measurement by a reflection method

Appl. Opt. 14:814-815; 1976

4.7 Other Methods

S. Tanaka, G. Tanaka, M. Hoshikawa, and N. Inagaki

Non-destructive refractive index profile identification of optical fiber preform utilizing x-rays

Digest, Sixth Eur. Conf. Opt. Commun., York, 165-168; 1980, IEE

*****

A. Ankiewicz, M. J. Adams, D. N. Payne, and F. M. E. Sladen

Parallel-beam excitation method for estimating refractive-index profiles in optical fibres

Electron. Lett. 14:811-812; 1978

A theoretical model is developed that demonstrates the presence of a ring in the far-field pattern when a graded-index fibre is excited by a collimated beam incident at a given radius from the core centre. The angular position of this ring can be used to obtain an estimate of the fibre refractive-index profile, provided a correction for the finite beam spot size is applied.

*****

K. Maeda and J. Hamasaki

A method of determining the refractive index profile of a lenslike medium

J. Opt. Soc. Am. 67:1672-1680; 1977

A simple method to obtain the fourth-order coefficient of the series expansion for the radial distribution of a lenslike medium is described. The coefficient is obtained by measuring the position of a discontinuity of the far-field intensity pattern. The relation between the coefficient and this position is calculated by using either the ray theory or the wave theory. By using a ray model, the position of the discontinuity and the macroscopic intensity distribution is easily obtained.

*****

L. Jeunhomme and J. P. Pocholle

Measurement of the numerical aperture of a step-index optical fibre

Electron. Lett. 12:63-64; 1976

We describe a simple method for measuring the numerical aperture of a step-index fibre. The value obtained by this method depends only on the index difference between the core and cladding, and it is then possible to deduce the index difference from this measurement.

*****

G. B. Brandt

Two wavelength measurements of optical waveguide parameters

Appl. Opt. 14:946-949; 1975

Optical waveguide parameters, guide index of refraction and thickness, can be measured from the knowledge of mode propagation constants at two different wavelengths. This method is as accurate as the two-mode method and can be used for both single-mode guides and multimode guides. The index of refraction of various optical components must be known at both the wavelengths; in cases where these indices are not directly available it is possible to interpolate this information from the known properties of other glasses. This paper describes the experimental and analytical aspects of the two-wavelength measurement technique.

5. CHARACTERIZATION OF DISCONTINUITIES (JOINTS, SPLICES, CONNECTORS, COUPLERS, DEFECTS)

5.1 General

N. K. Cheung and N. M. Denkin

An automatic inspection system for single fiber connector plugs

Tech. Digest, Symp. Opt. Fiber Meas.-1980 Boulder, 45-48; 1980, U.S. Govt. Printing Office

*****

P. DiVita and U. Rossi

Realistic evaluation of coupling loss between different optical fibers

J. Opt. Commun. 1:26-32; 1980

Coupling between two multimode optical fibers with different numerical aperture and core diameter and including lateral displacement is studied. Calculations are performed for fibers with any index profile and any power distribution among ray congruences. The propagation effects in the second fiber are also taken into account in a rigorous way. Finally asymptotic expressions of losses for small values of mismatch and error parameters are given together with a discussion on the minimization of coupling losses.

*****

K. S. Gordon and F. M. E. Sladen

Difficulties encountered in the measurement of optical fiber interconnection performance

Tech. Digest, Symp. Opt. Fiber Meas.-1980 Boulder, 67-72; 1980, U.S. Govt. Printing Office

*****

Ken-ichi Kitayama, Masaharu Ohashi, and Shigeyyuki Seikai

Mode conversion at splices in multimode graded-index fibers

IEEE J. Quantum Electron. QE-16:971-978; 1980

Mode conversions occuring at a splice in multimode graded-index fibers are investigated theoretically, and their effects on impulse responses are verified experimentally. The relation describing the mode behavior at a splice in existence of a geometrical offset and fiber parameter mismatches is derived by taking a skew ray as well as meridional ray into consideration. Then the mode transfer matrix is obtained to determine the variations in mode power distribution and impulse response due to the mode conversions occuring at a splice. The measured mean delay time difference between lower and higher mode pulse responses and baseband frequency response for spliced graded-index fibers are compared with the theory obtained from the transfer functions of individual fibers and the mode transfer matrix which describes the mode conversions at a splice due to a transverse displacement and fiber parameter mismatches.

*****

S. C. Mettler

A general characterization of splice loss for multimode optical fibers

Bell Sys. Tech. J. 58:2163-2182; 1979

The Gaussian point transmission model for calculating optical fiber splice loss is extended to the general case of splice loss between fibers which differ in one or more intrinsic parameters--core radius, index of refraction profile shape, and maximum index of refraction difference between core and cladding. The model is first verified for splices with index-of-refraction profile mismatch. The average difference between calculated and measured splice loss due to profile parameter mismatch is 0.04 dB. Comparisons are also made between calculated and measured splice loss for ten different splices with mismatch in all three intrinsic parameters. The average difference between the calculated loss and the average of several measured losses for these ten cases was 0.06 dB. The additional losses introduced by transverse offset measured for one set of mismatched fiber splices agree with the calculated values within 0.1 dB. Loss due to misalignment of elliptical core fibers is calculated and measured with agreement within 0.06 dB for the maximum loss case. Both the model and the experimental data show that, for a given percentage mismatch, index of refraction profile parameter mismatch and core ellipticity contribute significantly less to splice loss than mismatch of core radius or numerical aperture. A family of curves for splice loss vs transverse offset is presented for various numerical aperture mismatches and core radius mismatches, since these parameters are typically the largest components of splice loss in practical loss in practical fiber optic systems.

*****

S. Nemoto and T. Makimoto

Analysis of splice loss in single-mode fibres using a Gaussian field approximation

Opt. Quantum Electron. 11:447-457; 1979

By using a Gaussian field approximation to the fundamental mode in a single-mode fibre, a very simple formula is derived for the splice loss in the two fibres when transverse, longitudinal and angular misalignments exist simultaneously. It is shown that the effects of the three misalignments on the splice loss are more significant for step-index fibres than for parabolic-index fibres, and also that matching oil in the gap between the fibres is effective for the end separation, but produces a reverse effect for the tilt. Calculated coupling efficiency between step-index fibres is compared with the experimental data reported so far, and good agreement between them is observed.

*****

Y. Fujii and N. Suzuki

Precise angular misalignment measurement in optical fibre connector plugs

Electron. Lett. 14:243-245; 1978

A new precise measurement of angular misalignment in optical fibre connector plugs is described.

*****

M. J. Adams, D. N. Payne, and F. M. E. Sladen

Splicing tolerances in graded-index fibers

Appl. Phys. Lett. 28:524-526; 1976

Calculations are presented showing that, in general, a parabolic-index fiber is more sensitive to lateral misalignments within a splice than a step-index fiber. However, misalignments result in the excitation of leaky modes in graded-index fibers, and this can lead to optimistic joint loss measurements. Effective losses are given for various lengths of fiber following the splice, and it is shown that a parabolic-index fiber may appear more tolerant to misalignment than a step-index fiber when short lengths are used.

*****

D. Gloge

Offset and tilt loss in optical fiber splices

Bell Sys. Tech. J. 55:905-916; 1976

Transverse offset and angular misalignment (tilt) are serious causes of loss in multimode fiber splices. Our computation of these losses in multimode graded-index fibers reveals that the loss depends strongly on the power distribution in the fiber. We find that offsets of 0.1 of the core radius (or tilts of 0.1 of the fiber numerical aperture) cause a loss of 0.1 dB in the case of steady-state conditions, and between 0.34 and 0.38 dB if the power distribution is assumed as uniform. We compare these results with measured offset loss values and conclude that the steady-state distribution better reflects transmission line conditions than the uniform distribution.

*****

C. M. Miller

Transmission vs tranverse offset for parabolic-profile fiber splices with unequal core diameters

Bell Sys. Tech. J. 55:917-927; 1976

A geometrical optics model is presented that is based on defining a local numerical aperture as a function of fiber radius with a uniform power distribution. Transmission vs transverse offset characteristics for parabolic-profile fiber splices are calculated for unequal fiber-core diameters. We show that the often-used assumptions of equal-mode excitation, equal-mode attenuation, and no-mode coupling are not adequate to calculate realistic transmission vs offset characteristics. Splice-loss measurements with long fiber lengths on each side of the splice show less than the calculated sensitivity to small offsets and greater than the calculated sensivitity to large offsets.

5.2 Insertion Methods

P. Kaiser, W. C. Young, N. K. Cheung, and L. Curtis

Loss characterization of biconic single-fiber connectors

Tech. Digest, Symp. Opt. Fiber Meas.-1980 Boulder, 73-76; 1980, U.S. Govt. Printing Office

*****

U. Unrau and A. K. Agarwal

Modekontrollierte Messungen an Verzweigungsgliedern fur optische Nachrichtensysteme (Mode controlled measurements on couplers for optical telecommunications systems)

Digest, Mess in der opt. Nachrichten., Berlin, 173-175; 1980, VDE-Verlag

*****

Y. Daido, E. Miyauchi, T. Iwama, and No. Tokoyo

Measurement method of fiber connection loss using steady-state power distribution

Tech. Digest, Opt. Fiber Commun., Washington, 112-114; 1979, Opt. Soc. Am.

*****

A. H. Cherin and R. P. Rich

Measurement of loss and output numerical aperture of optical fiber splices

Appl. Opt. 17:642-645; 1978

An ensemble of optical fiber splices has been evaluated to determine how source launching conditions and length of fiber between the source, splice, and detector affect the splice loss and far field output NA. The loss of a splice is strongly dependent upon the energy distribution and NA of the beam at the input of the splice. For the range of NA's considered, the splice loss varied by 0.5 dB. The average NA at the output of the ensemble of splices was greater than its corresponding input NA by as much as 12%. The splice appears to act as a transformer converting the input energy distribution into one at the output that contains a greater amount of its energy in higher order modes. As a consequence of this, the loss of a fiber following the splice in a long transmission path is greater than the loss the fiber would exhibit if measured with steady state excitation conditions.

*****

T. C. Chu and A. R. McCormick

Measurements of loss due to offset, end separation, and angular misalignment in graded index fibers excited by an incoherent source

Bell Sys. Tech. J. 57:595-602; 1978

Transmission losses versus fiber end offset separation, and angular misalignment of graded index fibers excited by an incoherent source, have been measured in two independent experiments. The measurement setup, fiber diameter, and length were different in the two experiments, yet the measurement results are strikingly similar. The loss measurements clearly show that transverse offset is much more critical in connector and splice design than angular misalignment and end separation. Two-tenths of the fiber core radius in axial separation combined with 1° in angular misalignment may cause 0.5 dB loss.

*****

Iwao Hatakeyama and Haruhiko Tsuchiya

Fusion splices for optical fibers by discharge heating

Appl. Opt. 17:1959-1964; 1978

A new type of electric discharge fusion splicing apparatus for optical fibers offering several advantages is developed and evaluated. An average splicing loss of 0.10 dB is obtained for step-index multimode silica fibers with a 60-μm core diameter. Tolerances in discharge energy, fiber misalignment, compression force and stroke length during fusion, and end face conditions are discussed experimentally. No accurate fiber axis adjustment is necessary in this apparatus. Mechanical strength of the splice is also excellent.

*****

Jun-ichi Sakai and Tatsuya Kimura

Splice loss evaluation for optical fibers with arbitrary-index profile evaluation for optical fibers with arbitrary-index profile

Appl. Opt. 17:2848-2853; 1978

A method is presented for calculating offset and tilt losses for fiber splices with axially symmetric arbitrary-index profiles by approximating the profile with a staircase function. This method is applied to a large-core dual-mode fiber with zero intermodal dispersion as well as to single-mode fibers with step- and parabolic-index profiles. When a splice loss of 0.2 dB is permitted, the normalized offset misalignment is found to be D_N=0.635 for the dual-mode fiber at normalized frequency ν=4.605 and a power-law exponent α=4.5. The D_N value compares favorably with the values 0.560 and 0.614 for conventional step- and parabolic-index single-mode fibers, respectively. The dual-mode fiber is superior to the step- and parabolic-index fibers with respect to permissible splice offset tolerances.

*****

A. H. Cherin and P. J. Rich

Delay distortion characteristics of optical fiber splices

Appl. Opt. 16:497-500; 1977

The delay distortion characteristics of optical fiber splices are evaluated. Two 1.35-km graded index fibers with different transmission characteristics were each bisected and spliced together to determine how longitudinal and transverse displacement of fibers in a splice affect the delay distortion characteristics of a transmission path. The transmission characteristics of both the optical source and the fibers used play an important role in determining how delay distortion is affected by splice misalignment. The first fiber exhibited a great deal of mode mixing and a very small increase in delay distortion as the fibers were offset in the splice. In contrast, the second fiber exhibited very little mode mixing, but increased markedly in delay distortion as the fibers in the splice were displaced.

*****

A. H. Cherin and P. J. Rich

Multigroove embossed-plastic splice connector for joining groups of optical fibers

Appl. Opt. 14:3026-3030; 1975

To install and maintain successfully an optical fiber communications system, techniques for splicing individual and groups of optical fibers under field conditions must be developed. In this paper a technique for splicing groups of optical fibers with a one piece multigroove embossed plastic connector is described. Using 132-μm multimode fibers with 94-μm core diameters, the average transmission loss of the splice joints measured was 0.12 dB with a standard deviation of 0.11 dB and a range of loss values from 0.0 dB to 0.53 dB.

*****

D. L. Bisbee

Measurements of loss due to offsets and end separations of optical fibers

Bell Sys. Tech. J. 50:3159-3168; 1971

If fibers are to be coupled together by means of detachable connectors, there is a need to know how much light will be lost by misalignment or axial separation of the fiber ends.

Measurements were made of coupling efficiency from one fiber to another versus offset and end separation with an without index-matching liquid between the ends for a single-mode and a multimode fiber at λ-0.6328 μm. Graphs are presented for offsets as great as 3 radii and for end separations up to 127 μm. Maximum coupling efficiency of 97 percent was obtained, and about 50 percent was obtained with an offset of 1 radius.

5.3 OTDR Methods (See also 2.3)

A. J. Conduit, D. N. Payne, and A. H. Hartog

Optical fibre backscatter-loss signatures: Identification of features and correlation with known defects using the two channel technique

Digest, Sixth Eur. Conf. Opt. Commun., York, 152-155; 1980, IEE

*****

A. LeBoutet

Contribution to splice loss evaluation by the back-scattering technique: A statistical comparison with insertion loss data

Tech. Digest, Symp. Opt. Fiber Meas.-1980 Boulder, 77-80; 1980, U.S. Govt. Printing Office

*****

K. Okada, K. Hashimoto, T. Shibata, and Y. Nagaki

Optical cable fault location using correlation technique

Electron. Lett. 16:629-630; 1980

The letter describes a correlation based optical cable fault location technique which using a 1.3 μm wavelength, can detect a broken point 10 km distant from source.

*****

T. Asahara, Y. Ueno, M. Shimizu, and S. Naruse

Optical fiber fault locating method for long haul optical fiber communications link

Proc., Opt. Commun. Conf., Amsterdam, 14.5-1--14.5-4; 1979

A new optical fiber fault locating method which is suitable for in-service monitoring of long haul optical fiber communication link. The system accuracy was within 24 m in the field experimental system.

*****

B. Costa, F. Esposto, C. D'orio, and P. Morra

Splice loss evaluation by means of the back-scattering technique

Electron. Lett. 15:550-551; 1979

The results of a detailed experimental analysis on joint loss measurements by the back-scattering method are presented. A comparison with more usual insertion-loss technique is performed. High sensitivity and accuracy are found when measuring very similar fibres; a suitable procedure is indicated for measuring slightly different fibres.

*****

A. LeBoutet

Analysis of backscattering results applied to cable connection

Proc., Opt. Commun. Conf., Amsterdam, 9.6-1--9.6-6; 1979

That article deals with an analysis of results obtained by the backscattering technique applied to connectors. It tends to prove that the connector cannot be characterised in its junction plan only but has effects on the following fiber and is also affected both by the preceding fiber and injection conditions.

A more rigorous and realistic method of evaluation of the connector loss is also suggested for system application.

*****

P. Matthijsse and C. M. DeBlok

Field measurement of splice loss applying the back-scattering method

Electron. Lett. 15:795-797; 1979

A method is proposed to measure mean splice loss applying the back-scattering method from one end of the fibre link only. To eliminate the influence of the difference in backscattering properties of the spliced fibres, each backscattering coefficient is measured separately beforehand.

*****

P. Matthijsse and C. M. DeBlok

Measurement of splice insertion loss using the back-scattering method

Proc., Opt. Commun. Conf., Amsterdam, 9.5-1--9.5-4; 1979

To inspect the quality of splices in optical fiber links the backscattering method (optical time domain reflectometry) seems to be a powerful method. In this paper it is shown that this method is suited for measuring splice insertion loss only if special precautions are taken in view of the difference in backscatter coefficients.

*****

J. Guttman and O. Krumpholz

Location of imperfections in optical glass-fibre waveguides

Electron. Lett. 11:216-217; 1975

An echo-pulse technique for the location of fibre imperfections is described. The technique has been successfully applied to a plastics-coated Selfoc fibre and a plastics-coated silica-based fibre. Both showed a break. In the Selfoc fibre, an additional fibre defect was located. The same method may be used to measure rapidly the fibre length.

6. MODAL CHARACTERIZATION OF MULTIMODE FIBERS

6.1 General

O. G. Leminger and G. K. Grau

Near-field intensity and modal power distribution in multimode graded index fibres

Electron. Lett. 16:678-679; 1980

A relation between the modal power distribution and the near-field intensity is derived. Whereas the near-field intensity (averaged over all possible speckle patterns) is uniquely determined by the modal power distribution, it is impossible to derive a unique modal power distribution from a given near-field intensity. For special additional assumptions follow relations already known from literature.

*****

C. M. Miller and R. B. Kummer

Direct measurement of mode coupling effects using a mandrel wrap mode filter

Digest, Sixth Eur. Conf. Opt. Commun., York, 99-102; 1980, IEE

*****

Y. Daido, E. Miyauchi, T. Iwama, and T. Otsuka

Determination of modal power distribution in graded-index optical waveguides from near-field patterns and its application to differential mode attenuation measurement

Appl. Opt. 18:2207-2213; 1979

A technique is introduced that determines power distribution in fibers from the measured near-field pattern, assuming that: (1) the optical power distributes uniformly among degenerated modes with the same propagation constant, (2) enough modes are excited to ensure the validity of calculation by geometrical optics, and (3) the phase of each propagation mode has no correlation. Experiments verified that the fibers have the function of flattening power distribution among modes with the same propagation constant. This fact shows that assumption (1) does not severely limit the applicability of the technique. Wave optical calculation is done to determine the numbers of modes that must be excited to satisfy assumption (2). As an example of application of the technique, differential mode attenuation of graded-index fibers is determined from longitudinal variation of the measured near-field pattern.

*****

W. F. Love

Novel mode scrambler for use in optical-fiber bandwidth measurements

Tech. Digest, Opt. Fiber Commun., Washington, 118-120; 1979, Opt. Soc. Am.

*****

Ken-ichi Kitayama, Mitsuhiro Tateda, Shigeyuki Seikai, and Naoya Uchida

Determination of mode power distribution in a parabolic-index optical fiber: Theory and application

IEEE J. Quantum Electron. QE-15:1161-1165; 1979

A novel measurement meathod for determining mode power distribution in a multimode parabolic-index fiber is developed. Using this method, the mode power distributions are obtained in terms of the principal mode number by numerically processing the measured Fraunhofer diffraction patterns of the near-field patterns on an output fiber endface. As an example, differential mode attenuation of a multimode parabolic-index fiber is measured. It is confirmed experimentally that the method is practically applicable to the mode power distribution measurements in a parabolic-index fiber.

*****

S. Piazzola and G. DeMarchis

Analytical relations between modal power distribution and near-field intensity in graded-index fibres

Electron. Lett. 15:721-722; 1979

Modal power distribution is an important characteristic of optical fibres. Under the assumption that modes belonging to the same degenerate mode group carry the same amount of power, simple expressions are derived relating near-field intensity and modal power distribution in α-exponent index-profile optical fibres.

*****

W. J. Stewart

Method for measuring power distributions in graded and step-index fibers

Tech. Digest, Opt. Fiber Commun., Washington, 116-118; 1979, Opt. Soc. Am.

*****

F. T. Stone and P. H. Krawarik

Effects of different mode filters on optical-fiber measurements

Tech. Digest, Opt. Fiber Commun., Washington, 122-123; 1979, Opt. Soc. Am.

*****

H. R. D. Sunak, M. A. De Batista, and J. Neto

Measurements of mode conversion coefficients in multimode optical fibres

J. Inst. Electron. Telecomm. Eng. (India) 25:302-305; 1979

In order to assess quantitatively the quality of optical fibres preliminary measurements have been caried out with a very simple system, and the normalized mode conversion coefficient (D) has been calculated. The values of D obtained are of the order of $2x10^{-5}$ rad^2 m^{-1} for the fibres and these compare very favourably with the results obtained in other laboratories.

*****

L. Jeunhomme and J. P. Pocholle

Selective mode excitation of graded index optical fibers

Appl. Opt. 17:463-468; 1978

A method is described permitting excitation of a small number of modes in graded index fibers, the order of the launched mode being easily varied and determined. Using this launching technique, it is possible to determine the index profile and index difference of graded core fibers; results are compared with those obtained by other techniques. Other important fiber parameters, such as the differential attenuation and the differential propagation delay time as a function of the mode parameter, are also obtained, giving an insight into the fundamental propagation characteristics of the fiber.

*****

Kenichi Kitayama and Masahiro Ikeda

Mode mixing effects in optical fibers caused by sheathing and multistranding: Measurements

Appl. Opt. 17:3660-3664; 1978

Mode coupling coefficients were measured in a multimode stepindex fiber at different steps of the process of manufacturing a multistrand optical fiber cable. It was established that the mode coupling coefficients of the unsheathed fiber were relatively small and nearly the same for all the guided modes. By sheathing with nylon and multistranding, the mode coupling coefficients between lower-order modes increased rapidly due to microbends, while in the vicinity of the highest-order mode, they remained unchanged. From impulse response waveforms and baseband frequency responses, it was observed that mode mixing effects became more noticeable as the mode coupling coefficients increased. Also, it was found that the excess loss caused by microbends was relatively small.

*****

Kenichi Kitayama and Masahiro Ikeda

Mode coupling coefficient measurements in optical fibers

Appl. Opt. 17:3979-3983; 1978

The measuring method of the mode coupling coefficient was developed to apply to multimode fibers. It is shown that a mode coupling coefficient can be calculated from each mode group pulse waveform. Measurements were made with two cases of long-length and short-length multimode step-index fibers. As a result, it was observed that in the fiber sheathed by nylon, there existed a strong mode coupling in lower order modes. When it is assumed that this mode coupling is generated by microbendings, the correlation length and standard deviation of the curvature were estimated as 2.0 mm and $4.2x10^{-4}mm^{-1}$, respectively.

*****

Mitsunobu Miyagi, Shojiro Kawakami, Masaharu Ohashi, and Shigeo Nishida

Measurement of mode conversion coefficients and mode dependent losses in a multimode fiber

Appl. Opt. 17:3238-3244; 1978

*****

Richard Payne and Lionel O. Bouthillette

Effect of cladding modes on the far-field radiation pattern for a multimode step-index optical fiber

Appl. Opt. 17:2132-2134; 1978

*****

Hiroshi Shigesawa, Toyoki Matsuo and Kei Takiyama

Measurements of excitation condition and quantitative mode analysis in optical fibers

IEEE J. Quantum Electron. QE-16:36-44; 1980

The purpose of this paper is to describe an accurate method for determining the pulsed-power distribution along optical fibers and also to present a technique for measuring the launching conditions produced by an input laser beam. Experimental results demonstrate both the accuracy and the effectiveness of those methods for investigating the transmission characteristics of optical waveguides. Various factors having an important influence upon the accuracy are discussed, and appropriate methods for minimizing the systematic errors also are presented.

*****

K. Thyargarajan, Anurag Sharma, and A. K. Ghatak

Efficient coupling of incoherent light into optical fibers and bundles

Appl. Opt. 17:2416-2419; 1978

The excitation efficiencies of a few lower order modes in a W-type fiber have been studied when the modes are excited with tilted as well as off-set Gaussian beams. The effect of beam size, angle of incidence, the radius of curvature of the incident wavefront, and the off-axis displacement on the excitation efficiencies has been obtained. It is found that in order to couple maximum power into the fundamental mode, the incident wavefront must be plane and the beam must be incident axially along the fiber with a suitable value of the beam size.

*****

Hideaharu Tokiwa, Yasuharu Suematsu and Kazuhito Furuya

Estimation of coupling length in mode-coupled multimode optical fibers

Trans. IECE Japan E61:192-195; 1978

A method to estimate the coupling length of the fiber in which modes couple each other due to the random bending of fiber axis is given. The coupling length is estimated from the comparison of the measured transfer functicn to the theoretical one which is derived previously. The coupling length of a graded-index fiber is estimated to be about 0.8 km using this method. Further, the coupling length of recent graded-index fibers is presumed to be about several km. For step-index fibers, it is estimated to be in the range between 0.5-5 km.

*****

Masahiro Ikeda, Yasuji Murakami, and Kenichi Kitayama

Mode scrambler for optical fibers

Appl. Opt. 16:1045-1049; 1977

Mode conversion at a splice was measured. Even the best splice, whose transmission loss was less than 0.01 dB, caused a mode conversion equaling about 11% of the total power. Spliced fiber transmission characteristics were influenced by the splicing conditions. To avoid deviations in characteristics due to splices a simple and effective mode scrambler was fabricated. Its insertion loss was less than 0.3 dB for a laser diode. Each mode's output waveform was found to be the same as the total output waveform.

*****

Massahiro Ikeda, Akira Sugimura, and Tetsuhiko Ikegami

Multimode optical fibers: Steady state mode exciter

Appl. Opt. 15:2116-2120; 1976

The steady state mode power distribution of the multimode graded index fiber was measured. A simple and effective steady state mode exciter was fabricated by an etching technique. Its insertion loss was 0.5 dB for an injection laser. Deviation in transmission characteristics of multimode graded index fibers can be avoided by using the steady state mode exciter.

*****

S. Zemon and D. Fellows

Characterization of the approach to steady state and the steady state properties of multimode optical fibers using LED excitation

Opt. Commun. 13:198-202; 1975

A simple technique has been developed to characterize the approach to steady state and the steady-state properties of multimode fibers using LED excitation. Results are given for 6 mil Selfoc fibers whose far-field pattern for the steady state is in excellent agreement with a calculation by Marcuse. To first order, the steady-state mode distribution fits a simple model of uniform modal excitation of a fiber with a reduced numerical aperture.

*****

J. E. Midwinter and M. H. Reeve

A technique for the study of mode cut-offs in multimode optical fibres

Optoelect. 6:411-416; 1974

We describe a technique of using a variable wavelength source to study mode cut-offs up to a V value of 20 for the optical fibre by means of the radiated (scattered) power leaving the fibre. This allows the identification of individual modes in a fibre carrying up to 80 or 100 modes in all and provides a non-destructive method for the study of the length and bend dependence of the energy carried by the highest order modes.

Mustafa A. G. Abushagur and Nicholas George

Measurement of optical fiber diameter using the fast Fourier transform

Appl. Opt. 19:2031-2033; 1980

The variation of the fringe spacing of the far zone scattered intensity of an illuminated optical fiber has been plotted vs the scattering angle, theoretically and experimentally. A method for measuring fiber diameters by taking the Fourier transform of the scattering intensity is described. Theoretical and experimental results have been compared at various angles for different fiber diameters.

*****

D. H. Smithgall and C. M. Schroeder

A comparison of techniques to measure the diameter of lightguide fiber

Tech. Digest, Symp. Opt. Fiber Meas.-1980 Boulder, 41-44; 1980, U.S. Govt. Printing Office

*****

L. S. Watkins and R. E. Frazee, Jr.

High speed measurement of the core diameter of a step-index optical fiber

Appl. Opt. 19:3756-3762; 1980

The forward scattering light pattern from a clad optical fiber illuminated perpendicular to its axis is characteristic of the outer diameter, the core diameter, and their respective refractive indices. This pattern is detected by a diode array detector to produce a video signal representation of the scattering pattern. Electronic circuits have been developed to analyze the scattering pattern and detect the angular position of the modulation characteristics of the pattern. This provides a determination of the core to outer diameter ratio of the fiber. Using linearization circuits and the outer diameter measurement signal, linear measurement signal voltages of both core ratio and core diameter are derived. The measurement of core ratio refers to a particular radius vector and means that determinations of circularity and concentricity can also be made.

*****

R. Bouillie and L. Jeunhomme

Measurement techniques for physical characteristics of optical fibers

Conf. Rec., Int. Conf. Commun., Boston, 36.1.1-36.1.4; 1979, IEEE

We present here a review of the relevant characteristics of optical fibers and of the corresponding measurement techniques, essentially based on the conclusions of CCITT study group XV. We also describe a recent and new approach for characterizing the information carrying capacity of the fiber by its intermodal dispersion.

*****

Kashiko Kodata, Haruko Takenka

Measurement of mechanical deformation of dielectric fibres by light scattering method

Opt. Quantum Electron. 11:497-505; 1979

This paper describes an experimental method to detect quantitative changes of both refractive index and diameter of unclad dielectric fibres, such as fused silica fibre and nylon 6 fibre, due to tensile stress. The technique employed here is based on the variation in the position of a fringe in back-scattered light, which is generated when a laser beam is incident at a right angle to the axis of the fibre. This procedure makes it possible to measure refractive index, diameter and ellipticity to within an accuracy of 0.048%, 2.6% and 0.05%, respectively.

*****

D. Marcuse and H. M. Presby

Automatic geometric measurements of single-mode and multimode optical

Appl. Opt. 18:402-408; 1979

An automatic method has been developed to measure the outer diameter, the core diameter, the degree of elipticity, and the core concentricity of both single mode and multimode optical fibers. A short length of fiber (~1 cm) is prepared by scoring and breaking, and one end face is observed with a microscope utilizing transmitted light illumination. The image is processed with a computer-controlled automatic video-analysis-system which tracks and locates the outer and core boundaries, performs various fitting routines, calculates the desired quantities, and produces a plot of fiber boundaries and core offset, all within 3 min. The reproducibility of the measurements depends upon the quality of the sample and is on the order of 0.1 μm for eccentricity values of good fiber samples with surfaces free from dirt and cracks and on the order of 1/2% for the core radius.

*****

A. van der Meulen and L. Strackee

Accurate determination of fiber radii in the hypermicrometer range by multiwavelength laser light scattering

Appl. Opt. 18:3751-3757; 1979

Laser light scattering from fused silica fibers, with radii in the hypermicrometer range (1-10 μm) has been studied. The vertical polarized component of the scattered radiation has been observed over an angular range from 2° to 135°, the angular resolution being 0.3°. The experiments were carried out using the discrete visible wavelength lines from a Kr^+ ion laser. The experimentally observed total number of minima in the angular range between 0° and 90° has been compared with computations based on the model of an infinitely long circular cylinder. In this way it is possible to perform a fast and accurate (better than 1%) determination of fiber radii without the necessity of calibration, over a large range of physical acceptable refractive indices. Alternatively, measuring the near forwardscattering over a carefully predetermined collecting aperture suffices to estimate quickly the fiber radius to within 5.0% over the same refractive index range. When the refractive index is known beforehand, the accuracy of both methods can be improved to within 5.0% and 2%, respectively. When a full comparison with the theoretical angular scattering curves is performed, the fiber radius is obtained with an accuracy better than 0.1%, as well as the refractive index. The full curves are calculated by Dave's computational procedure adapted for cylinders.

*****

Charoon Saekeang and Pak L. Chu

Diameter determination of graded-index optical fibers from backward-scattered pattern

Appl. Opt. 18:3276-3281; 1979

The backscattered pattern of an optical fiber with arbitrary refractive-index profile is used to determine the fiber diameter. Two methods are presented: the fiber diameter can be determined either by noting the position of a particular fringe maximum or by counting the total number of fringes in the pattern. This method is fast in that it does not require any mechanical moving part, and the measurement error is 1%. This method is based on the prior knowledge of the refractive-index profile of the fiber, but it is shown that the error incurred by assuming the wrong profile is less than 1%. It is also shown in this paper that the method can be used to monitor the diameter variation while the fiber is being pulled. This is done by tracking the displacement of a particular fringe. It is shown that this method is also applicable to fibers with elliptical cross section.

*****

Noriyoshi Shibata, Kaname Jinguji, Masao Kawachi, and Takao Edahiro

Nondestructive structure measurement of optical-fiber preforms with photoelastic effect

J. Appl. Phys. (Japan) 18:1267-1273; 1979

The photoelastic effect is used to measure nondestructively the structure parameters of optical-fiber preforms. An He-Ne laser beam is introduced perpendicular to the preform axis, the transmitted beam is optically retarded by residual stresses in the preform, and the optical retardation is measured. A procedure for determining the core diameter and the refractive-index profile from the measured optical retardation is presented. It is applied to a step-index preform and a graded-index preform fabricated by the M.C.V.D. (Modified Chemical Vapour-phase Deposition) technique.

*****

Hiroshi Takahashi, Seiji Shibuya, and Toshiaki Kuroha

Applicative investigation of X-ray non-destructive inspection technique for measurement of core diameters and germanium doping concentration profiles of optical fiber preforms

Proc., Opt. Commun. Conf., Amsterdam, 14.4-1--14.4-4; 1979

X-ray non-destructive inspection technique was applied to measurement of the germanium doping concentration profiles of optical high-silica glass fiber preforms non-destructively. Due to the big difference of the mass absorption coefficient between germanium and other elements such as silicon, phosphorous and boron, the core diameter of the preform can be determined, and quantitative information of germanium doping concentration profiles can be obtained. An excellent point of this method is capability of application to opaque porous preforms which are fabricated by the Vapor-phase Axial Deposition (VAD) and the Outside Vapor-phase Oxidation (OVPO) processes.

*****

E. Johansen and P. V. H. Sabine

Structural characteristics of optical fibres

A.T.R.-Aust. Telecomm. Rev. 12:25-39; 1978

The first part of this paper outlines the modified chemical vapour deposition fibre fabrication process. Various inherent structural characteristics of the fibres are related to particular manufacturing operations and techniques for investigating these characteristics are discussed. The scanning electron microscope, and in particular the secondary electron imaging and microprobe modes, is shown to provide a powerful analytical tool for examining the physical and compositional properties of fibres. Measurement of the near-field intensity distribution is found to be a rapid and convenient technique for investigating som important optical transmission properties of the fibre--most notably, for determining the refractive index profile. The primary purpose of this paper is to show that a greater understanding of the fibre can be obtained by correlating results from all three techniques. Practical results illustrating this correlation procedure are presented. The particular fibres described are experimental step index and step index-barrier layer fibres manufactured at the AWA Research Laboratory under contract to Telecom Australia.

*****

P. H. Krawarik and L. S. Watkins

Fiber geometry specifications and its relation to measured fiber statistics

Appl. Opt. 17:3984-3989; 1978

Fiber quality requirements can be specified in a number of ways; the most typical is to state a required diameter and give a tolerance band to allow for manufacturing variations. Actual fiber diameter statistics have been shown to be close to Gaussian for certain range of fiber lengths. The fiber statistics are discussed showing the bounds of stationarity and their relation to fiber specifications. Thus the fiber statistics in terms of standard deviation and sample length can be related to the specification. Not only variations within one fiber are important, but also from fiber to fiber. Thus, the effect of mean-to-mean differences in fibers and their influence in meeting fiber specification for given standard deviations are considered. In considering these factors, the following conclusions are made. There is a bandwidth which can be related to the fiber drawing process, and measurement of fiber diameter for the purpose of characterization must be made at a rate greater than this bandwidth to guarantee fiber quality. Since fiber drawing is a predominately random process, specifications should be written which relate to a statistical description of the process. If a tolerance band is used for the specification of fiber diameter, it ought to comprise two parts. One part will allow for the random fiber diameter variations. The second part must provide for the deviations of the mean diameter of each complete length from the nominal.

*****

David H. Smithgall, Laurence S. Watkins, and Ralph E. Frazee, Jr.

An optical fiber diameter measurement system using forward scattered light

IEEE Trans. Ind. Electron. and Control Instrum. IECI-25:108-112; 1978

Forward scattering of light by an optical fiber produces an interference fringe pattern in which the fringe spacing is inversely proportional to the fiber diameter. An electrooptic system has been developed to produce and detect this scattering pattern, thus providing a measure of fiber diameter.

The system measures the fiber diameter by a fringe counting techique with an accuracy of ±0.2 μm over a range of diameters 50-150 μm. Measurement are updated at a 1-kHz rate. The system design allows the fiber to move laterally within a one-centimeter diameter window without affecting the measurement accuracy.

The signal-processing circuitry employs a microprocessor to format the measurement output in engineering units to a digital display, and as an analog output suitable for feedback control of the fiber diameter. In addition, the processor computes the mean and standard deviation of an arbitrary length of fiber, providing a measure of the quality of the fiber drawn.

*****

A. R. Tynes, R. M. Derosier, and W. G. French

Measurement of single-mode fibre core-cladding concentricity

Electron. Lett. 14:113-115; 1978

Single-mode fibre core-cladding concentricity has been measured by using a fibre splicing technique. In this technique a short length of fibre is broken in two and one length is rotated about its own axis α degrees with respect to the other length and then the two lengths are spliced together. The splice loss when $\alpha = 180°$ is a direct measure of the fibre butt-joint offset and hence also of the concentricity of the core and the cladding. A submicrometre sensitivity for this measurement has been achieved.

*****

M. Ito, M. Okada, and T. Miya

Automatic measurements of fiber parameters: Dimensional nonuniformity and refractive index profiles

Electron. Commun. Lab. Tech. J. (Japan) 26:2585-2589; 1977

Structural property measurement methods for preform-rods and fibers have been studied. An automatic system for a dimensional nonuniformity measurement, using backscattering pattern analysis, has made possible a rapid and precise measurement of rod diameters, core diameters, structure distortions and torsions. An automatic system for a refractive index profile measurement in interferometry has also been made, using an ITV and automatic image processing.

*****

D. Marcuse and H. M. Presby

Optical fiber coating concentricity: Measurement and analysis

Appl. Opt. 16:2383-2390; 1977

Backscattering of laser light that is incident at right angles to the axis of an optical fiber is utilized to evaluate the degree of eccentricity of a plastic jacket on the fiber. An analytical treatment of the problem based on ray optics is shown to be in excellent agreement with experiments, which are capable of detecting core-to-jacket offsets on the order of 1 μm.

*****

D. Marcuse and H. M. Presby

Measurement of optical fiber coating concentricity

Tech. Digest, Opt. Fiber Trans. II, Williamsburg, PD2-1-PD2-4; 1977, Opt. Soc. Am.

*****

H. M. Presby

Detection of geometric perturbations in optical fibers

Appl. Opt. 16:695-700; 1977

A sensitive, quick, and nondestructive method to assess the short range geometrical uniformity of optical fibers is presented. The technique is based on an analysis of the backscattered light arising from a beam that is incident at right angles to the fiber's axis and is capable of measuring diameter variations on the order of 0.1 μm. Geometric perturbations arising in selected fibers pulled with oxy-hydrogen torch, electric furnace, and CO_2-laser techniques are shown in an almost instantly read snapshotlike form. The production and detection of intentionally introduced short range diameter variations are also demonstrated.

*****

D. H. Smithgall and L. S. Watkins

A high speed optical fiber diameter measurement and characterization system

IEEE J. Quantum Electron. QE-13:19D-20D; 1977

*****

D. H. Smithgall, L. S. Watkins, and R. E. Frazee, Jr.

High-speed noncontact fiber-diameter measurement using forward light scattering

Appl. Opt. 16:2395-2402; 1977

The forward scattering of light by an optical fiber produces an interference fringe pattern, and the fringe period is inversely proportional to the fiber diameter. An electrooptic system has been developed to produce and detect this scattering pattern to provide an instrument which will measure fiber diameter during the drawing operation. The system measures the fiber diameter at a 1-kHz rate with a precision of 0.25 μm and an accuracy of ±0.25 μm over a range of 50-150- μm diams. The instrument allows the fiber to move laterally in a 1-cm diam window maintaining the above accuracy. The system can be calibrated optically and does not need a standard fiber for this procedure. The instrument has been used for months without the need for recalibration. In addition to the digital diameter output, the system employs a microprocessor to compute mean and standard deviation values for various sample lengths and provides suitable signals for feedback control of fiber diameter.

*****

P. L. Chu

Determination of the diameter of unclad optical fibre

Electron. Lett. 12:14-16; 1976

It is shown that the backward-scattered interference pattern of an unclad optical fibre can be adequately described by Airy's rainbow theory. A formula is derived from which the diameter of the fibre may be calculated if the position of the raimbow maximum is measured from the scattered pattern. The error involved in this method is less than 3%. Comparison between this method and Marcuse's method is also made, and it is found that the present method can lead to a more reliable result.

*****

P. L. Chu

Determination of diameters and refractive indices of step-index optical fibres

Electron. Lett. 12:155-157; 1976

A method is given whereby the radii and refractive indices of the core and cladding of a step-index optical fibre can be determined uniquely from the backward-scattered pattern. The technique is based on the analysis of various rays that contribute to the formation of the back-scattered pattern.

*****

W. Eickhoff and O. Krumpholz

Determination of the ellipticity of monomode glass fibres from measurements of scattered light intensity

Electron. Lett. 12:405-407; 1976

A nondestructive method is proposed to determine the core ellipticity of a monomode fibre from measurements of the scattered light intensity.

*****

Sandor Holly

Lateral interferometry monitors fiber diameter

Laser Focus 12:58-60; 1976

*****

H. M. Presby

Ellipticity measurement of optical fibers

Appl. Opt. 15:492-494; 1976

The experimental aspects of a sensitive, nondestructive, and noncontacting method to measure the noncircularity of dielectric cylinders are presented. The technique makes use of the variation in the position of a fringe in the backscattered light arising from a beam that is incident at right angles to the cylinder's axis, as the cylinder is rotated. The method has been applied to optical fibers, and ellipticities as small as 0.997 have been measured. The results are in agreement with photomicroscopy measurements and with theoretical predictions.

*****

John W. Y. Lit

Radius of uncladded optical fiber from back-scattered radiation pattern

J. Opt. Soc. Am. 65:1311-1315; 1975

The back-scattered pattern produced by a plane-polarized beam incident normally on a large uncladded optical fiber can be used to determine the refractive index and the radius of the fiber. The geometric-optics method is used to analyze the pattern. A new procedure to find the radius of the fiber is proposed. The procedure can make use of nearly the whole of the back-scattered pattern, without need to measure exactly the positions of all of the individual fringes. Special attention is given to the limits of accuracy.

*****

H. M. Presby

Refractive index and diameter measurements of unclad optical fibers

J. Opt. Soc. Am. 64:280-284; 1974

A new method is presented to determine the refractive index and the diameter of unclad optical fibers. The technique is based on an analysis of the back-scattered light when a beam from a cw laser impinges upon the fiber. A geometrical-optics analysis shows that the position of a sharp cutoff in the radiation pattern determines the refractive index, whereas the distance between certain successive minima gives the diameter. The theory is compared to experimental observations, with excellent agreement.

*****

L. S. Watkins

Scattering from side-illuminated clad glass fibers for determination of fiber parameters

J. Opt. Soc. Am. 64:767-772; 1974

The theoretical characteristics of the scattered-light pattern from a clad glass fiber illuminated by a laser beam perpendicular to its axis agree closely with results of experimental measurements of the scattered light. A simplified geometric ray-tracing technique shows that for fibers with medium and small core sizes, specific angle ranges of the scattering pattern provide determinations of fiber diameter independent of core parameters. Measurements of the fringe modulation give relatively sensitive determinations of core diameter. Light scattering is a useful technique for determining the diameters of both clad and unclad fiber. Total-diameter determinations have accuracies of ±0.2 μm and core diameters, ±0.5 μm for 0.02 refractive-index difference between core and cladding.

*****

L. G. Cohen and P. Glynn

Dynamic measurement of optical fiber diameter

Rev. Sci. Instrum. 44:1749-1752; 1953

This paper describes a novel technique for monitoring the outside dimensions of clad or unclad optical fibers. An oscillating mirror is used to deflect a laser beam with constant velocity across a fiber in order to measure the time interval during which the fiber intercepts the beam and casts a shadow on a photodetector. For 110 μ fibers, individual measurements made every 1/60 sec are repeatable within a spread of ± 1% from the 330 μsec mean time interval (rms deviation ≈ ±0.6%). Results are displayed in digital form, but can be converted to an analog signal for use in a servo loop to control the pulling rate of fiber drawing machines. An additional feature of the technique is that fibers with non-circular cross sections can be monitored by making sequential diameter measurements along orthogonal axes of the fiber.

R. Auffret, L. Pophillat, and Y. Kervarrec

Appareillage de terrain pour la mesure de l'attenuation et de la band passante des liaisons optiques (Field measurement set for attenuation and bandwidth of optical links)

Electron. Lett. 16:798-799; 1980

The letter deals with a quite simple apparatus capable of bandwidth and insertion loss measurements of installed optical links. The performance is such that the measurement is possible whatever the distance between two regenerators.

*****

K. Hiepe-Wohlleben, M. Kaiser, R. Rossberg

Feldmassige Dampfungs - und Dispersionsmessung an einem Lichtleit-Erdkabel (Field measurements of attenuation and dispersion in lightguide underground cable)

Digest, Mess. in der opt. Nachrichten., Berlin, 103-107; 1980, VDE-Verlag

*****

R. Novak

Prazise fledtaugliche Methode und Apparatur fur die Dampfungsmessunger an PTT Glasfaser Anlangen (Precise field suitable method and apparatus for attenuation measurement on PTT glass fiber installations)

Digest, Mess in der opt. Nachrichten., Berlin, 108-115; 1980, VDE-Verlag

*****

W. Eickhoff, O. Krumpholz, E. Pfeiffer, M. Rode, and E. Weidel

Field measurement equipment for fibre optical waveguide cables

Digest, Fourth Eur. Conf. Opt. Commun., Genova, 179-182; 1978

Fibre measurement equipment for loss, dispersion and fault location is described. Insertion loss measurements in excess of 60 dB are possible with a reproducibility of about ± 0.1 dB. The dynamic range for pulse response measurements is more than 50 dB using light pulses with a 3 dB pulse width of 300 ps. Fault location measurement can be performed with an accuracy of 1 m. The equipment developed is compact, portable and easy to handle.

*****

L. Jeunhomme and J. P. Pochelle

Selective mode excitation of graded index optical fibers

Appl. Opt. 17:463-468; 1978

A method is described permitting excitation of a small number of modes in graded index fibers, the order of the launched mode being easily varied and determined. Using this launching technique, it is possible to determine the index profile and index difference of graded core fibers; results are compared with those obtained by other techniques. Other important fiber parameters, such as the differential attenuation and the differential propagation delay time as a function of the mode parameter, are also obtained, giving an insight into the fundamental propagation characteristics of the fiber.

*****

K. C. Byron, G. J. Cannell, I. S. Few, and R. Worthington

Field measurement of fiber optic cables

Proc., Third Eur. Conf. Opt. Commun., Munich, 34-36; 1977

V. A. Bhagavatula, W. F. Love, and D. B. Keck

Electron. Lett. 16:695-696; 1980

A technique to measure the local (2-3 mm) values of cutoff wavelength λ_c in single-mode waveguides is described. The technique, insensitive to the length of waveguide used, involves the spectral measurement of refracted power. The feasibility of using the cutoff wavelength determined by this technique to predict the zero dispersion wavelength is also studied.

*****

P. D. Lazay

Effect of curvature on the cutoff wavelength of single mode fibers

Tech. Digest, Symp. Opt. Fiber Meas.-1980 Boulder, 93-96; 1980, U.S. Govt. Printing Office

*****

F. Mohr and U. Zwick

Messung der Eigenschaften von Monomodefasern (Measuring the characteristics of monomode fiber)

Digest, Mess in der opt. Nachrichten., Berlin, 121-125; 1980, VDE-Verlag

*****

M. Monerie, P. Lamouler, and L. Jeunhomme

Polarisation mode dispersion measurements in long single mode fibres

Electron. Lett. 16:907-908; 1980

A frequency domain determination of polarisation mode dispersion in single mode fibres is described, which allows one to obtain directly the group delay difference for long fibres. The results of such measurements are shown on a birefringent fibre with elliptical cross-section which maintains an extinction ratio between linearly polarised eigenstates greater than 10 dB over 1 km.

*****

M. Monerie, P. Lamouler, and L. Jeunhomme

Measurement of polarization mode dispersion

Digest, Sixth Eur. Conf. Opt. Commun., York, 110-112; 1980, IEE

*****

C. Pask and R. A. Sammut

Experimental characterisation of graded-index single-mode fibres

Electron. Lett. 16:310-311, 1980

A simple and accurate method is presented for experimental characterisation of graded-index single-mode fibres using their far-field radiation patterns and the "equivalent-step" method.

*****

I. Sasaki, D. N. Payne, R. J. Mansfield, and M. J. Adams

Variation of refractive-index profiles in single-mode fibre preforms measured using an improved high-resolution spatial-filtering technique

Digest, Sixth Eur. Conf. Opt. Commun., York, 140-143; 1980, IEE

*****

J. Streckert

Charakterisierung und Messung der Kennwerte einwelliger Glasfasern (Characterizing and measuring the characteristic value of single mode glass fiber)

Digest, Mess in der opt. Nachrichten., Berlin, 126-128; 1980, VDE-Verlag

*****

Akara Sugimura, Kazuhiro Daikoku, Nobuyuki Imoto, and Tetsuo Miva

Wavelength dispersion characteristics of single-mode fibers in low-loss region

IEEE J. Quant. Elect. QE-16:215-225; 1980

Wavelength dispersion characteristics of single-mode silica fibers in a very low-loss region, including zero dispersion wavelengths, are studied in detail using a "difference method." Wavelength dispersion of single-mode fibers is compared for fibers with same material dispersion but with different waveguide structure. Material dispersion is evaluated by extracting waveguide dispersion from experimental results. Effects of waveguide dispersion on the zero dispersion wavelength of the single-mode fiber in a longer wavelength region are clearly analyzed. Single-mode fiber design consideration is given from the wavelength dispersion point of view.

*****

K. I. White, B. P. Nelson, J. V. Wright, M. C. Brierly, and A. Beaumont

Characterisation of single mode fibres

Tech. Digest, Symp. Opt. Fiber Meas.-1980 Boulder, 89-92; 1980, U.S. Govt. Printing Office

*****

Ernst Brinkmeyer

Spot size of graded-index single-mode fibers: Profile-independent representation and new determination method

Appl. Opt. 18:932-937; 1979

A simple nondestructive method is described for determining the spot size ω_0 (width of the fundamental mode)--one of the most important quantities to characterize monomode optical fibers. The theory involves the definition of effective values of core radius and normalized frequency. Thereby, graded-index fibers can be replaced by equivalent step-index fibers. The experiment consists in illuminating the fiber perpendicularly to its axis and determining the position of the first minimum in the diffraction pattern. In this way, just one measurement yields ω_0 regardless of the index profile and for any operating wavelength, provided the cutoff wavelength is known.

*****

Kazuo Hotate and Takanori Okoshi

Measurement of refractive-index profile and transmission characteristics of a single-mode optical fiber from its exit-radiation pattern

Appl. Opt. 18:3265-3271; 1979

A new exit-radiation pattern method for measuring the refractive-index profile of a single-mode fiber is proposed and used experimentally. In this method the profile is computed from the far-field exit-radiation pattern of the HE_{11} mode at the end of the single-mode fiber. This method can be applied to a cabled fiber, and the propagation constant, field profile, and group delay of the HE_{11} mode, and the single-mode limit can be obtained as well as the index profile. The principle, computer simulations, experimental setup, and experimental results are first described. The profile obtained shows a good agreement with that obtained from the interference fringe pattern measured before drawing the fiber. Computations of the group delay of the HE_{11} mode and the single-mode limit from the measured exit-radiation pattern are discussed.

*****

Yasuyuki Kato, Ken-ichi Kitayama, Shigeyuki Seikai, and Naoya Uchida

Novel method for measuring cutoff wavelength of HE_{21}, TE_{01}, and TM_{01} modes

Electron. Lett. 15:410-411; 1979

A new measurement method for the cutoff wavelength of HE_{21}-, TE_{01}- and TM_{01}-modes using a polariser is described. The experimental results show that higher measurement accuracy and sensitivity are obtained compared with the previous method.

*****

Yasuji Murakami, Akio Kawana, and Haruhiko Tsuchiya

Cut-off wavelength measurements for single-mode optical fibers

Appl. Opt. 18:1101-1105; 1979

A new technique has been proposed for direct measurement of the cut-off wavelength, at which the first higher-order mode disappears. It uses a change of a near-field pattern of a fiber, which is excited by a variable wavelength source. The cut-off wavelength can be measured with ±5-nm accuracy. The most suitable fiber length for precise measurement is 10-20 mm. It is found, furthermore, that the first higher-order mode under the condition near cut-off rapidly attenuates because of waveguide imperfections, in which the loss due to core-cladding boundary distortions is the most dominant.

*****

J. P. Pocholle

Single mode optical fiber characterisation by the LP_{11} mode radiation pattern

Opt. Commun. 31:143-147; 1979

We describe a method for determining the V-value from the far-field radiation pattern of dual mode optical fibers (this method is an extension of the work by Gambling et al. for the LP_{11} modes). The method involves measurements of the maximum radiation angle and the angle of the first minimum. Curves are presented which can be used with dual mode fibers, determining the core diameter, the refractive index difference between core and cladding, as well as the V-value in the single mode regime for longer wavelength operation with the help of dispersion curves of the dopant materials.

*****

Yasuji Murakami and Haruhiko Tsuchiya

Bending losses of coated single-mode optical fibers

IEEE J. Quantum Electron. QE-14:495-501; 1978

Peaks appear in bending losses of coated single-mode fibers due to interference between the guided mode and rays which are radiated from the guided mode and are reflected at cladding-coating boundary. This paper reports derivation of bending loss formulas for coated slab waveguides and coated fibers. Plane wave concepts are also used to explain the appearance of the loss peaks. Measurements were performed by using two coated single-mode fibers. The agreement between theory and experimental results is found to be excellent. It is possible to obtain the refractive index difference from measured peak wavelengths.

*****

Mitsuhiro Tateda

Single-mode-fiber refractive-index profile measurement by reflection method

Appl. Opt. 17:475-478; 1978

A new technique for measuring the refractive index profile of single-mode fibers based on the reflection method is described, and experimental results are demonstrated. When the core radius of a test fiber is only a few times larger than the laser beam spot size, the reflected power distribution does not indicate the refractive index correctly. However, the true index profile can be calculated from the beam spot size and the reflected power distribution with high accuracy: 0.3-μm spatial resolution and 5% relative refractive-index resolution are obtained for practical single-mode fibers.

*****

W. A. Gambling, D. N. Payne, H. Matsumura, and S. R. Norman

Measurement of normalized frequency in single-mode optical fibres

Electron. Lett. 13:133-135; 1977

It is shown that methods of measuring the normalised frequency in single-mode fibres through observation of mode cut-off wavelengths give erroneous results. This is because the various loss mechanisms which exist in a practical fibre can have an appreciable effect near cut-off.

*****

W. A. Gambling, D. N. Payne, H. Matsumura, and R. B. Dyott

Determination of core diameter and refractive-index difference of single-mode fibres by observation of the far-field pattern

Microwaves, Opt. Acoust. 1:13-17; 1976

A method is described for determining unambiguously, from the far-field pattern of single-mode fibres, the core diameter and the refractive-index difference between core and cladding. It involves measurements only of the half-power width of the main lobe and the width of the first minimum. Universal curves are presented that can be used with single-mode fibres or any fibre operating in the single-mode regime. Independent determinations of core diameter over the range 4-8 μm by an etching technique are in excellent agreement with those obtained from the far-field pattern.

*****

Yutaka Katsuyama, Masamitse Tokuda, Naoya Uchida, and Motohiro Nakahara

New method for measuring V-value of a single-mode optical fibre

Electron. Lett. 12:669-670; 1976

A simple method is proposed for the direct measurement of the V-value for a single-mode optical fibre. This method consists of measurement of loss peaks, corresponding to cutoff wavelengths of the higher modes, which are easily observed for a fibre with a bend.

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS TN-1043	2. Performing Organ. Report No.	3. Publication Date June 1981

4. TITLE AND SUBTITLE

The Characterization of Optical Fiber Waveguides

A Bibliography with Abstracts, 1970 - 1980

5. AUTHOR(S)

G. W. Day, Editor

6. PERFORMING ORGANIZATION (*If joint or other than NBS, see instructions*)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (*Street, City, State, ZIP*)

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

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.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

Bibliography, measurements, optical fibers, optical communications

13. AVAILABILITY

[X] Unlimited

☐ For Official Distribution. Do Not Release to NTIS

[X] Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

72

15. Price

$4.25

☆ U.S. GOVERNMENT PRINTING OFFICE: 1981 — 777-002/1254 Region No. 8

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH—The Journal of Research of the National Bureau of Standards reports NBS research and development in those disciplines of the physical and engineering sciences in which the Bureau is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Bureau's technical and scientific programs. As a special service to subscribers each issue contains complete citations to all recent Bureau publications in both NBS and non-NBS media. Issued six times a year. Annual subscription: domestic $13; foreign $16.25. Single copy, $3 domestic; $3.75 foreign.

NOTE: The Journal was formerly published in two sections: Section A "Physics and Chemistry" and Section B "Mathematical Sciences."

DIMENSIONS/NBS—This monthly magazine is published to inform scientists, engineers, business and industry leaders, teachers, students, and consumers of the latest advances in science and technology, with primary emphasis on work at NBS. The magazine highlights and reviews such issues as energy research, fire protection, building technology, metric conversion, pollution abatement, health and safety, and consumer product performance. In addition, it reports the results of Bureau programs in measurement standards and techniques, properties of matter and materials, engineering standards and services, instrumentation, and automatic data processing. Annual subscription: domestic $11; foreign $13.75.

NONPERIODICALS

Monographs—Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NBS under the authority of the National Standard Data Act (Public Law 90-396).

NOTE: The principal publication outlet for the foregoing data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St., NW, Washington, DC 20056.

Building Science Series—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NBS under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The standards establish nationally recognized requirements for products, and provide all concerned interests with a basis for common understanding of the characteristics of the products. NBS administers this program as a supplement to the activities of the private sector standardizing organizations.

Consumer Information Series—Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

Order the **above** *NBS publications from: Superintendent of Documents, Government Printing Office, Washington, DC 20402.*

Order the **following** *NBS publications—FIPS and NBSIR's—from the National Technical Information Services, Springfield, VA 22161.*

Federal Information Processing Standards Publications (FIPS PUB)—Publications in this series collectively constitute the Federal Information Processing Standards Register. The Register serves as the official source of information in the Federal Government regarding standards issued by NBS pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

NBS Interagency Reports (NBSIR)—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Services, Springfield, VA 22161, in paper copy or microfiche form.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-215

U.S.MAIL

SPECIAL FOURTH-CLASS RATE
BOOK