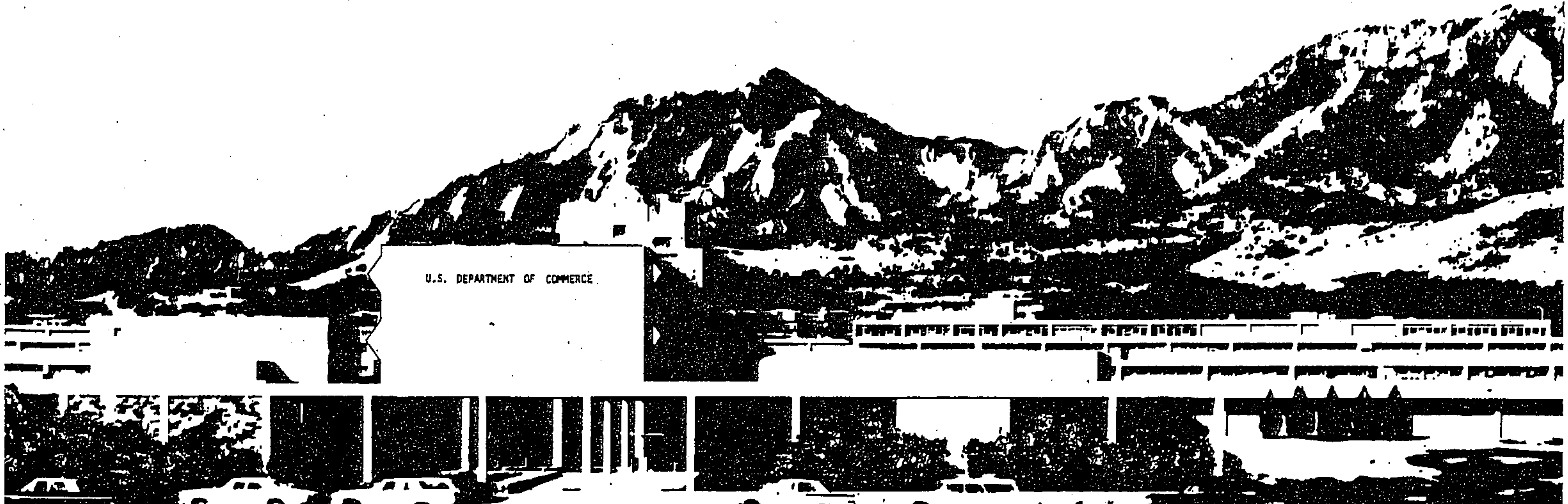
NBS SPECIAL PUBLICATION 720

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

Technical Digest Symposium on Optical Fiber Measurements, 1986

Sponsored by the National Bureau of Standards
in cooperation with the IEEE Optical Communications Committee
and the Optical Society of America



MULTIMODE FIBER SYSTEMS CHARACTERIZATION

I.P. Vayshenker, D.R. Hjelme, and A.R. Mickelson
Department of Electrical and Computer Engineering
University of Colorado
Boulder, Colorado 80309

Introduction

When designing a multimode fiber system (MFS) one should take into consideration the mode-dependent properties of the components of the system. Lack of a design tool for fiber-optics networks makes the problem more difficult. However, one can describe a MFS using mode dependent matrices for each component of the system and obtain the system response as a product of these matrices and the input vectors [1]. This method has been used by Evers [2,3] to characterize couplers and connectors, and by Mickelson et al [4,5] for fusion splices and microbends. To our knowledge there exist no work on transmission matrices for fibers, but only mode dependent attenuation measurements [6]. The purpose of this paper is to give an accurate measurement technique to obtain the transmission matrix for arbitrary fiber optic connectors attached by multimode fibers, and apply these techniques to various connector/fiber combinations.

Theoretical Relations

The mode transmission matrices can be obtained from power loss and near-field measurements. Using the mode continuum approximation [7], one can relate the near field, I(s), to the modal power distribution p(R). For an azimuthally symmetric fiber with arbitrary index profile $n^2 = n_1^2[1-2\Delta f(s)]$ this relation is $I(s) = \frac{V^2}{\pi} \int_{f^{1/2}(s)}^{1} p(R)R\,dR$ where $s = r/a$ is the normalized radial coordinate, $R^2 = \frac{1}{2\Delta}(1 - \beta^2/n_1^2k^2)$ is the mode parameter and $V = n_1ka\sqrt{2\Delta}$. It should be mentioned that this approximation is valid provided that the linewidth, $\delta\lambda$, of the exciting source satisfy $\delta\lambda/\lambda > \sqrt{2\Delta}/(ka\,N_1)$, where $N_1 = n_1 - \lambda\frac{dn}{d\lambda}$ is the material group index. The total power, P_i, in the modes with R values between R_i and R_{i+1} are given by $P_i = \int_{R_i}^{R_{i+1}} p(R)\,m(R)\,dR$ where $m(R) = V^2R[f^{-1}(R^2)/a]^2$ is the modal density. Dividing R-space into n intervals, one can define a power vector $P = [P_1, P_2, \cdots P_n]^T$ (T for transpose). The input, $P^{(i)}$, and output, $P^{(0)}$, vectors can then be related by the mode transmission matrix T [1] as $P^{(0)} = T\,P^{(i)}$. The diagonal elements of T represent the fraction of power incident on the system in the modes of one R-interval which remains in the same R-interval, and the off-diagonal elements represent the fraction of power coupled between the modes.

For a fiber, T would obviously be length dependent. In a fiber with only absorption and Rayleigh scattering it would be reasonable to assume T to be a diagonal matrix with elements $T_{ii} = e^{-\gamma_i z}$, where γ_i corresponds to the differential mode attenuation (DMA) coefficient $\gamma(R)$ [6]. But as shown in [6], other mode dependent effects such as mode coupling and coupling to radiation modes gives γ a length dependence and worse, it is extremely hard to determine from measured data. These problems could be overcome if we define a length independent matrix A as $T = e^{-ZA}$ for the fiber. A would correspond to a two-variable DMA coefficient $\gamma(R,R')$ as suggested in [6].

Measurement of the Transmission Matrix

The transmission matrix contains in general n^2 independent elements and to obtain these, one needs n^2 independent measured quantities. This could be obtained using selective excitation to create n independent input vectors $P_k^{(i)}$ and measure $P_k^{(0)}$. Then T is obtained from $T = [P_1^{(0)}, \ldots, P_n^{(0)}][P_1^{(i)}, \ldots, P_n^{(i)}]^{-1}$. The diffraction limit poses a severe restriction on how many independent inputs one can generate. Increasing n would then make T unstable, and there should be an optimal number of excitations, n. Some authors [2,3] recommend n = 3 and others [4] n = 2. In this paper n = 2 is used. It should be pointed out that the resulting matrix T is very sensitive to the power loss ratios $|P_k^{(0)}|/|P_k^{(i)}|$. The larger n and hence the less independent inputs, the more sensitive T is to this ratio.

The measurement set-up is shown in Fig. 1. Selective excitation is generated by varying the 3 parameters of the launch system. These parameters can be defined by $u = \frac{r_s}{a}$, $\rho = \frac{a_{beam}}{a}$, $\tau = \frac{NA_{beam}}{NA_{fiber}}$ where r_s is radial launch position, a_{beam} is the beam radius, NA_{beam} is the effective numerical aperture of the launching system. In the experiment $\rho = .14$, $\tau = .68$, $u = 0, .64$ were used. Fig. 2 shows the calculated (using the theory of [6]), p(R) and I(s) for these parameters. To find the input vector $P_k^{(i)}$, the measured near-field intensity of a short fiber, stripped for cladding modes, was used. Similarly for the connector a short fiber was used at the output end.

Beside errors in the power measurements and the near-field measurements, other error sources can affect the results. Among these are fiber end quality and alignment problems [8] and leaky modes [9, 10, 11]. According to Petermann [11], the leaky mode correction factor given in [9.10] is very sensitive to non-circular perturbations of the fiber. The correction therefore becomes very uncertain and in this work it is not used.

Results

The following combinations were under test: Long fiber-connector-long fiber (lcl) and short fiber-long fiber (sl). Fig. 3 illustrates the measured near-fields and derived modal power distributions for the sl combination. To reduce the noise in the data, the measured near-fields were filtered using a fast-fourier transform and a properly chosen cut-off frequency. Next the filtered near-fields were fitted to a 12th order polynomial (only even powers of s) and p(R) was calculated and the power vectors formed. The transmission matrix for the fiber is found from the sl combination to be

$$AL = \begin{bmatrix} .70 & -.13 \\ -.09 & .74 \end{bmatrix} \qquad (*)$$

The total transmission matrix, T_{lcl}, for the lcl combination were found to be

$$T_{lcl} = \begin{bmatrix} .21 & .05 \\ .04 & .12 \end{bmatrix}$$

Using this matrix and the matrix for the fiber, the connector transmission matrix can be found using the relation $T_{lcl} = e^{-AL}\, T_c\, e^{-AL}$. The resulting connector matrix becomes

$$T_c = \begin{bmatrix} .84 & .01 \\ .04 & .48 \end{bmatrix}$$

This matrix is in good agreement with the matrices found by Evers [3]. From the fiber transmission matrix A it is possible to find the steady-state distribution. We can write $P^{(0)} = e^{-AL} P^{(i)} = \sum_{n=1}^{n} \mu_k \cdot P^{(i)} \mu_k e^{-\lambda_k L}$ when μ_k and λ_k are the eigenvectors and eigenvalues of A. After a long propagation distance only the vector corresponding to the smallest eigenvalue will survive, i.e., it is the steady state distribution [12]. The matrix (*) has the following eigenvalues and eigenvectors

$$\mu_1 = \begin{bmatrix} 1.0 \\ .7 \end{bmatrix}; \quad \mu_2 = \begin{bmatrix} 1.0 \\ -1.0 \end{bmatrix} \quad L\lambda_1 = .61, \quad L\lambda_2 = .83.$$

The eigenvalue λ_1 corresponds to a steady state loss of 2.63 dB/km. The corresponding power vector μ_1, is in agreement with the steady state modal distributions found in [4,5].

Acknowledgment

This work is funded by a grant from AMP, Inc., Harrisburg, PA.

References

[1] G.T. Holmes, "Estimation of concatenated system response based on measured transfer functions for low and high order modes," in Prod. Seventh European Conf. on Opt. Commun (Copenhagen, Denmark), Sept. 1981, pp. 3.4-1 - 3.4-4.

[2] G. Evers, "Measurement of mode transition matrices of quasi-step-index optical fiber components," SPIE vol. 500, Fiber Optics: Short-Haul and Long-Haul measurements and application II, 1984.

[3] G. Evers, "Mode transition matrices for fiber-optic connectors," El. Lett. 21, 401-2, 1985.

[4] A.R. Mickelson, M. Eriksrud, S. Aamlid, N. Ryen, "Role of the Fusion Splice in the Concatenation Problem; J. Light Technology, Vol. LT-2, No. 2, pp. 126-138, 1984.

[5] A.R. Mickelson, "Backscatter Readout from Serial Microbending Sensors," J. Light Tech., Vol. LT-2, pp. 700-09, 1984.

[6] A.R. Mickelson and M. Eriksrud, "Mode-dependent attenuation in optical fibers," J. Opt. Soc. Am., vol. 73, No. 10, pp. 1282-1290, 1983.

[7] A.R. Mickelson and M. Eriksrud, "Mode-continuum approximation in optical fibers," Opt. Lett., vol. 7, pp. 572-574, 1982.

[8] D. Rittich, "Practicability of Determining the Modal Power Distribution by measured Near and Far Fields," J. Light Technology, Vol. LT-3, No. 3, pp. 652-661, 1985.

[9] M.J. Adams, "Correction factors for the determination of optical-fiber refractive-index profiles by the near-field scanning technique," El. Lett. 12, pp. 281-83, 1976.

[10] M.J. Adams, "Length-dependence effects due to leaky modes on multimode graded-index optical fibers", Opt. Commun. 17, pp. 204-09, 1976.

[11] K. Petermann, "Uncertainties of leaky mode correction for near-square-low optical fibers," El. Lett. 18, pp. 513-14, 1977.

[12] D. Marcuse, Theory of Dielectric Optical Waveguides, Academic Press, 1974.

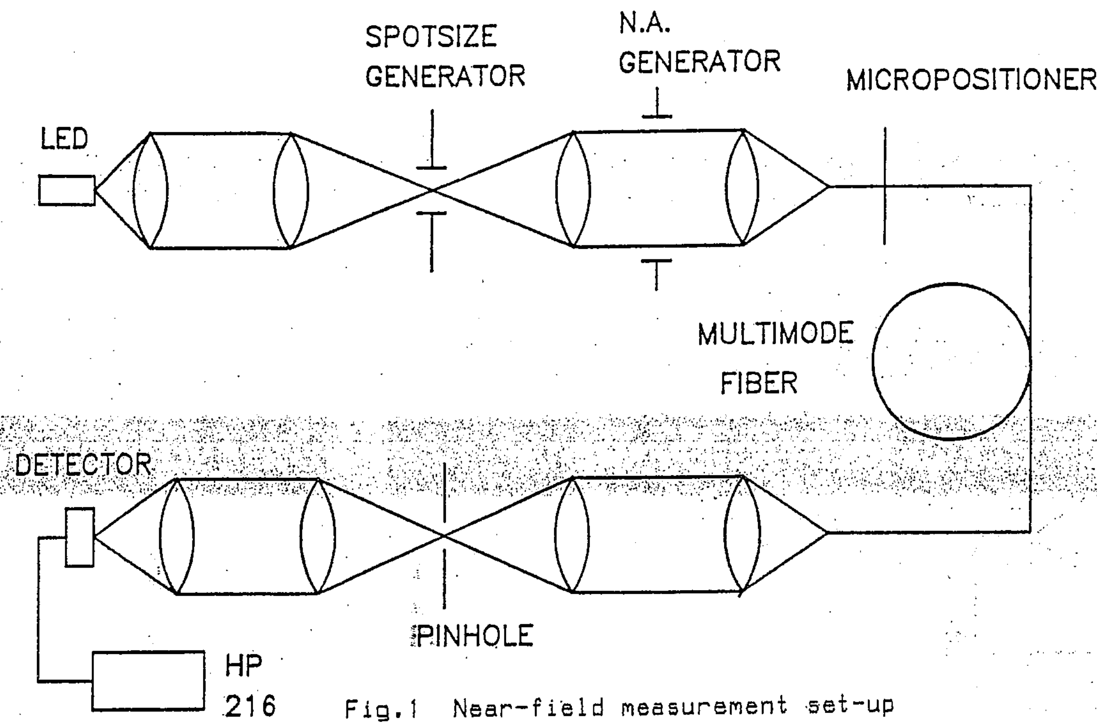


Fig.1 Near-field measurement set-up

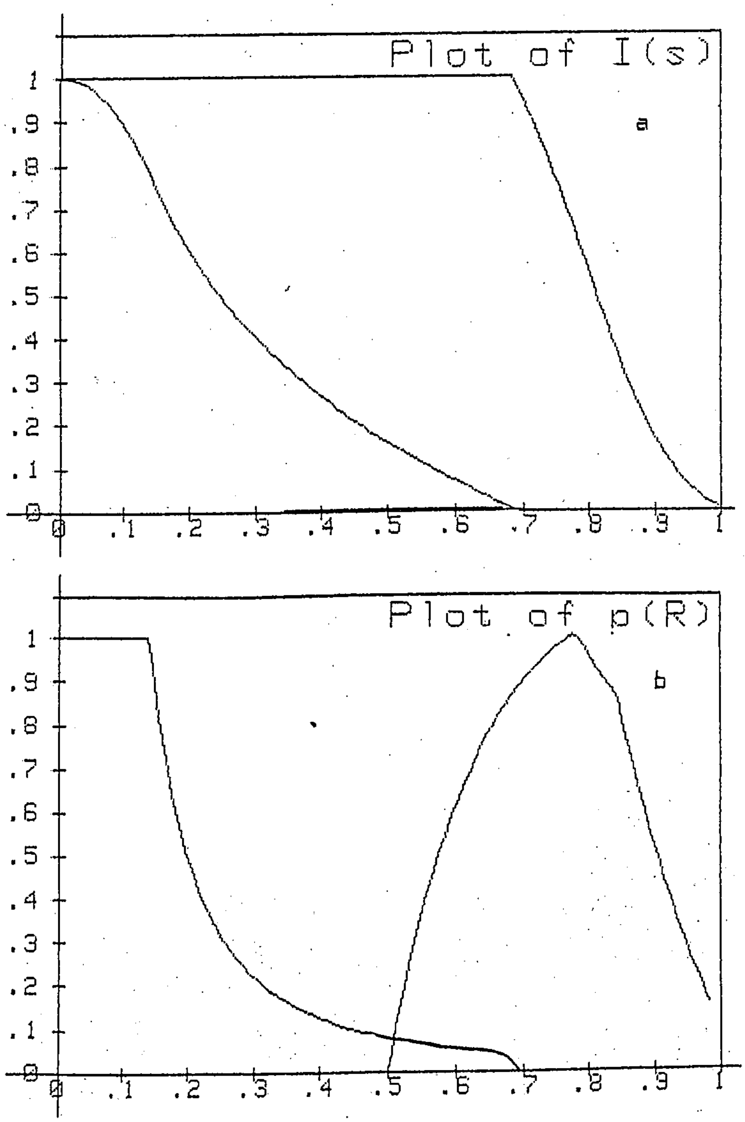


Fig.2 Theoretical I(s)-a and p(R)-b for the excitions used in the experiment

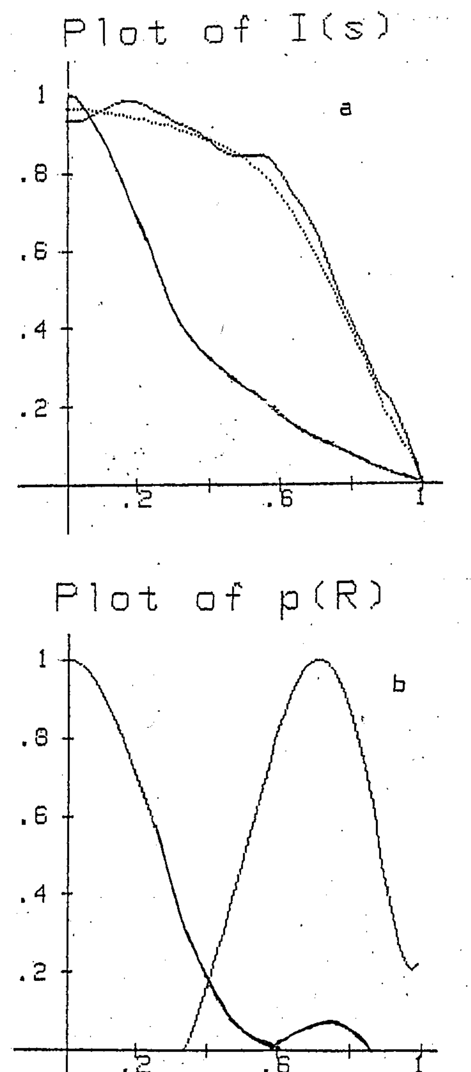


Fig.3 Measured I(s)-a and p(R)-b for the long fiber