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The cover was designed by GWA Design Consultants and is a photographic solution, the ends of the optical fibres being yellow to emphasise light passing through.

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Announcement

During the planning phase of the Conference it became clear that the interest in this subject was sufficient to demand a series of Conferences. Consideration was given to initiating an International or a European series.

After consultation with representatives from the European countries, the USA and Japan, it was recommended that this Conference should be the first of a series of European Conferences with the following Conference to be held in 1976 in France and a subsequent one in Germany in 1977.

Although the future Conferences will be organised on a European basis, it is the intention to strongly encourage participation on an international basis by invitation of the speakers and session chairmen, and by presentation of papers.

C. P. Sandbank
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PRINCIPLES OF OPTICAL FIBER TRANSMISSION

D. Gloge*

To describe modern fibers, one must find a compromise between the inadequate simplicity of the dielectric slab analog and the complexity of the rigorous field solutions of the circular cylindrical rod [1]. Most useful is a concept which can be stripped of irrelevant information from the beginning, applies to the classical step-index as well as to graded-index profiles, and can be reduced to a few clear pictures and diagrams. By combining suitable pairs of the HE and the EH solutions of the cylindrical rod, for example, one gains a simple formalism of mode character which sidesteps bizarre beat phenomena that occur in fibers, but are of no concern when direct detection is used [2]. In a next step, one can decompose the fields so gained into locally plain wavelets. Lines drawn along the wave normals, represent "mode-equivalent" rays which follow spiralling paths bouncing off the core walls. Projected onto the fiber end, such paths typically describe re-iterative star patterns. These patterns and their distortion in distorted fibers yield meaningful insight into the mode behavior.

Of course, rays and wave vectors are derivable from the mode parameters directly without knowledge of the mode field. This is as true for the step profile as for any (gently) graded index profile. In fact, in case of the graded index, the local wave vector often serves as the starting point for field computations (Wentzel-Kramers-Brillouin method [3]). So far, these arguments have not taken us beyond classical ray optics. However, a formal extrapolation of the wave vector concept is valid in regions where one or more of its components appear imaginary (which foils the classical ray concept). The magnitude of the imaginary component determines the evanescent field decay in that direction [4]. A phenomenon explainable in these terms is the strong cladding field decay of many fiber modes at cutoff. (This behavior is in sharp contrast with the modes of the slab which are unbounded at cutoff.) Arguments based on the cladding wave vector also explain the selective leakage instrumental in suppressing modes other than the fundamental in near-single-mode operation (W-fiber [5]).

Single-mode operation avoids the signal impairment that results from group delay differences in multimode fibers, but apart from the requirements it imposes on the optical source, single-mode operation compounds the difficulties of fiber splicing and cabling. The latter task requires fibers that are insensitive to "microbending", a distortion of the fiber axis (imposed from the outside) that causes a signal loss both in single- and multimode operation as a result of a power transfer

*Bell Laboratories, Crawford Hill Laboratory, Box 400, Holmdel, New Jersey 07733

from propagating modes to undesired or lossy modes [6]. To control this effect, one must attempt to place the beat wavelength associated with the critical transfer into a range where the fiber is stiff enough to resist distortions. Unfortunately, optimum microbending control and the best splicing characteristics are usually incompatible objectives and require a compromise; single-mode operation, if desired, further narrows the options of this compromise.

If one chooses multimode operation, one has to cope with the spread of the modal group delays. One can compute the delays (in seconds per unit length) from the frequency derivative $d\beta/d\omega$ of the modal propagation constant β by way of a very general variational principle which links these quantities to a (weighted) average of the magnitude of the local wave vector $kn(x,y)$ in the waveguide cross section [7]. More specifically

$$\beta \frac{d\beta}{d\omega} = \int kn \frac{d(kn)}{d\omega} p(x,y)dxdy$$

where the integration is over the entire cross-sectional area. If one interpretes $p(x,y)$ as the probability of a ray to traverse the cross section at (x,y), the equation above quickly reduces to the formula generally used to compute the time of flight along a geometrical ray path. In more general (and more accurate) terms, however, $p(x,y)$ is the modal power density normalized for unit power flow through the cross section.

The best signal performance results for an index profile $n(x,y)$ for which the integral on the right is (as closely as possible) proportional to β for all the modes of the guide so that $d\beta/d\omega$ is nearly invariant with mode number. Finding this profile is a difficult optimization problem affected also by the material-related interdependence between n and $dn/d\omega$ [8]. Some knowledge of this interdependence and an intelligent choice of trial functions are necessary. No reason exists, however, why the profile cannot be designed to such precision that the transmission of hundreds of Megabit per second is feasible over the full repeater spacing that modern low-loss fibers offer.

This summary is necessarily sketchy. I hope it will arouse an interest in a more detailed talk. It is my intention to emphasize successful concepts, perceptions, and techniques of analysis rather than to present a finished theory of fibers. On the other hand, I hope that exemplary demonstrations of such concepts and techniques at work will illuminate the more urgent problems of modern fiber technology and suggest ways of solving them.

REFERENCES

1. Snitzer, E.: Cylindrical dielectric waveguide modes. J. Opt. Soc. Am. Vol 51, No. 5, May 1961, pp. 491-505.
2. Gloge, D.: Weakly guiding fibers. Appl. Opt. Vol 10, No. 10, October 1971, pp. 2252-2258.
3. Kurtz, C. N. and Streifer, W.: Guided waves in inhomogeneous focusing media. IEEE Trans. Microwave Theory and Tech. Vol MTT-17, May 1969, pp. 250-263.

4. Maurer, S. J. and Felsen, L. B.: Ray methods for tapped and slightly leaky modes in multilayered or multiwave regions. IEEE Trans. Microwave Theory Tech. Vol. MTT-18, September 1970, pp. 584-595.
5. Kawakami, S. and Nishida, S.: Anomalous dispersion of new doubly clad optical fiber with a low-index inner cladding. IEEE J. Quantum Electr. Vol QE-10, No. 12, December 1974, pp. 879-887.
6. Marcuse, D.: Theory of dielectric optical waveguides, Academic Press, New York, 1974, pp. 162 and 235.
7. Chase, K. M.: On wave propagation in inhomogeneous media J. Math. Phys. Vol 13, 1972, p. 360.
8. Olshansky, R. and Keck, D. B.: Material effects on minimizing pulse broadening, Proc. of the Topical Meeting on Opt. Fiber Transmission, Williamsburg, January 1975, pp. TuC5/1-3.

RAY ANALYSIS OF PULSE DISTORTION DUE TO SCATTERING

Allan W. Snyder *

Coupled power equations[1] have proven to be a valuable tool for the analysis of pulse distortion due to imperfections on optical waveguides. These equations were derived from coupled mode theory using statistical averaging methods. However, coupled mode theory is unnecessary when the waveguide is overmoded. Then, the simplest ray analysis applies, in which irregularities are characterized by their differential scattering cross section σ_d and cladding loss is included via Fresnel's classical laws for reflection, leading to[2]

$$\frac{\partial I}{\partial z} + \frac{1}{v}\frac{\partial I}{\partial t} + \alpha I = \int_0^{\theta_c} S(\theta,\theta')I(\theta',z)\ \theta' d\theta' \tag{1}$$

$$\alpha = \alpha_a + N\sigma_{tot} \tag{2}$$

$$S(\theta,\theta') = N\int_0^{2\pi} \sigma_d(\theta,\theta',\phi)\ d\phi \tag{3}$$

$$v(\theta) = c\ \cos\theta \cong c(1+\theta^2/2) \tag{4}$$

I is the energy distribution within a hollow annular cone bounded by angles θ and $\theta + d\theta$ where θ and ϕ are the spherical polar angles referred to the fibre axis, i.e. θ is the inclination of the ray to the fibre axis and ϕ the aximuthal angle. N is the number density of scatterers per unit volume and σ_{tot} is the total scattering cross section. θ_c is the complement of the critical angle.
Equation (1) reduces to a diffusion equation for highly forward directed scatterers. For Rayleigh scatterers, there is negligible distortion but significant attenuation due to scattering, i.e.

$$I(\theta,z,t) \cong e^{-\alpha z}\ I(\theta,0,t-z/v)\ . \tag{5}$$

We discuss the condition under which eq. (1) is equivalent to the coupled power formalism. Several types of scattering mechanisms are analysed for arbitrary illumination and the Greens function for Rayleigh scatterers is discussed.

References:

1 Marcuse, D.: Theory of dielectric optical waveguides (Academic, 1974) Chapter 5, p.201.

2 Snyder, A.W., Mitchell, D.J., and Pask, C.: Pulse propagation in multimode optical fibres. Electronics Letters (submitted).

*Institute of Advanced Studies, Department of Applied Mathematics, The Australian National University, Canberra, A.C.T. 2600, Australia.

PULSE BROADENING IN MULTIMODE OPTICAL FIBERS

J A Arnaud *

The broadening of optical pulses propagating in multimode optical fibers can be evaluated by comparing the times of flight of pulses moving along rays excited by the source. To evaluate this time of flight, it is essential to know the radial variation of the ratio of the local phase to group velocity in the material.[1] We shall call this variation the "inhomogeneous dispersion" of the fiber.

We shall give first a closed form expression of the impulse response of a fiber when the square of the refractive index is a constant plus a power of the distance from axis. This profile was first discussed by Gloge and Marcatili.[2] However, inhomogeneous dispersion was neglected. The impulse width obtained from our expression (see below), which takes inhomogeneous dispersion into account, is in substantial agreement with that reported by Olshansky and Keck[3] who, however, do not give the impulse response. Next, we give the impulse width for small but otherwise arbitrary departures of the square of the refractive index profile from a square-law.[4] This more exact expression is needed when the deviation of the profile from square law goes beyond r^4 terms, or when the square of the refractive index is not a linear function of dopant concentration. Application to germania doped fibers will be done on the basis of recent refractive index measurements by Fleming[5]. Finally, we shall compare the pulse broadening obtained by solving numerically the scalar Helmholtz equation for stepped profiles to that obtained by ray (or WKB) methods.

A few algebraic results relevant to the above discussion are displayed below. Let us first assume that the square of the free wavenumber $k(r,\omega) \equiv (\omega/c)\, n(r,\omega)$ has the form

$$K(R,\Omega) = \begin{cases} K_o(\Omega) - K_k(\Omega)\, R^k, & R < A \\ K_o(\Omega) - K_k(\Omega)\, A^k, & R \geq A \end{cases} \quad (1)$$

where capital letters denote the squares of the corresponding small letters, namely $K \equiv k^2$, $R \equiv r^2$, $A \equiv a^2$, $\Omega \equiv \omega^2$ and a is the core radius (with the notation in Ref. 2 and 3, $2k \equiv \alpha$). Assuming that the source is lambertian, the impulse response is found to be exactly (within ray optics)

$$P(t) = (K_o A/2)\beta \left[(1-\beta^2)/(1-\beta_s^2)\right]^{1/k}\left[D' - (1-D')\beta^{-2}\right] \quad (2a)$$

*Bell Laboratories, USA