

ON THE ENHANCEMENT OF FIBER BANDWIDTH BY DISTORSIONS.

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I - Introduction

Personick¹ first noted that optical pulses propagating in multimode fibers broaden at a rate proportional to $L^{1/2}$ beyond some coupling length L_c that can be made arbitrarily small by increasing the fiber distortion. It follows that the fiber bandwidth can be increased by a factor of $(L/L_c)^{1/2}$. It remains an intriguing possibility that the bandwidth of multimode fibers, particularly step-index fibers, can be drastically increased by such distortions. In uniform step-index fibers, pulses broaden at a rate as large as 50 ns/km. The irregularities that occur naturally reduce somewhat this rate of broadening^{2,3}. But a much larger reduction is expected on theoretical grounds if the fiber distortion spectrum exhibits a sharp cut-off at high spatial frequencies, because the guided modes are then thoroughly mixed, but are not coupled to the radiation modes. Marcuse has shown that the product of the square of the pulse-broadening improvement factor R and the excess loss L is independent of the distortion strength. This product, R^2L , however, depends on the index profile (e.g., step-index or square-law) and the type of distortion (e.g., uniform, peaked, or rapidly decreasing). It is not known yet how low the product R^2L can be, because previous theories are somewhat inaccurate, as we shall discuss below, and also because the limitations that fabrication techniques impose on the distortion spectra have not been sufficiently investigated. Note that step-index glass fibers made by the double crucible method are significantly less expensive than fibers fabricated by the CVD process and can have losses as low as 5 dB/km. There is therefore an economical motivation to increase the bandwidth of step-index, or mildly-graded multimode fibers. Distortions would also make the grading process less critical. The main objective of our work is thus to find on theoretical grounds how low the product R^2 can be, and to actually fabricate broadband low-loss step-index fibers. This objective has not yet been attained. But we report an expression which is simple, general, and exact (within the WKB approximation) for the effect of microbends (section II), and a fabrication and measuring technique for intentionally distorted fibers (section III), that will enable us to answer the basic questions raised above.

II - Theoretical results

The first detailed theoretical results were obtained from the coupled mode theory, the guided modes being considered coupled by the axial irregularities of the fiber, and the mode numbers being treated as continuous variables. It now appears that rigorously equivalent results can be obtained from ray theory. Because the ray formalism is simpler than the modal formalism, no approximation needs to be made. The rate of pulse broadening can be obtained by integrating time along the ray trajectories⁴. One can show also that it is a consequence of the central-limit theorem that the impulse response of distorted fibers tends to be gaussian for large lengths. In what follows, we shall nevertheless use the modal language.

The axial (z) rate of change of the power $Q(\mu, \alpha, z)$ is mode μ, α (azimuthal and radial mode numbers, respectively) is given by the self-adjoint diffusion equation

$$\frac{\partial Q}{\partial z} = \frac{\partial}{\partial \alpha} D_0 \frac{\partial Q}{\partial \alpha} + \frac{\partial}{\partial \alpha} D_1 \frac{\partial Q}{\partial \mu} + \frac{\partial}{\partial \mu} D_1 \frac{\partial Q}{\partial \alpha} + \frac{\partial}{\partial \mu} D_2 \frac{\partial Q}{\partial \mu} \quad (1)$$

Thus, any distortion is fully characterized by just three functions of μ and α , namely D_0, D_1 and D_2 .

The cross-terms on the right-hand side of Eq.(1), which are sometimes forgotten, are at least as important as the other two terms. Another common error is to assume that Q depends only on the principal (or compound) mode number $m \equiv \mu + 2\alpha$. This assumption admittedly simplifies the equation, but it is in general not justified because, in square-law fibers, degenerate modes are not coupled by microbending (selection rule) and thus, the powers in modes of equal m do not equalize. In fact, the exact solutions are now known in terms of Bessel functions and Legendre polynomials. They involve both the principal mode number m and μ (or α). For profiles other than square-law, and specially for step-index profiles, the modes of propagation are not degenerate, even approximately. Indeed, modes are degenerate when the azimuthal ray period ϕ is equal to π . But clearly, for step-index profiles, ϕ can take all values from 0 to π . Furthermore, the simplification presently discussed (Q a function of m only) would hold only if the spectral density of the curvature process were very large at low spatial frequencies; but there are no compelling evidence that this is the case in practice. Finally, for peaked distortion spectra, couplings between nonadjacent modes cause the radiation patterns to exhibit a series of plateaus⁵ that are overlooked in simpler theories. It is therefore important to check the validity of the assumptions made in previous works by comparing them with a more rigorous theory.

The D_0, D_1, D_2 functions in Eq. (1) were given in simple closed forms by one of us⁶ for arbitrary profiles and arbitrary curvature spectra. We shall write down here only the explicit result for a step-index fiber and a uniform curvature spectral density γ . We have, setting $\Delta n/n \equiv \Delta$

$$\frac{\Delta}{\gamma} \frac{\partial P}{\partial z} = - \frac{\partial P}{\partial \epsilon} + \frac{\partial^2}{\partial \epsilon^2} (\epsilon P) + \frac{1}{12} \frac{\partial^2}{\partial v^2} \{ (1 + 2 v^2 / \epsilon) P \} + \frac{\partial^2}{\partial \epsilon \partial v} (v P) \quad (2)$$

The power P is here considered a function of $\epsilon \equiv (\theta/\theta_c)^2$ { θ being the angle of the ray to axis and $\theta_c = (2\Delta)^{1/2}$ }, and v , a normalized azimuthal mode number. Equation (2) is to be solved with the condition that $P = 0$ when $\theta = \theta_c$ as shown in the insert in Fig.1. Numerical results are shown in Fig.1 for two different excitation conditions, using a straightforward iteration procedure. The number of sample points in the ϵ, v plane was 1250. The slope of the curves tend to a steady state microbending loss of 6.5 (γ/Δ) dB/unit length. This is slightly larger than previously calculated values. One may at first feel that a small error on the microbending loss is not so important in practice because the distortion parameter (γ) is usually not known accurately. However, a small change in the statistical mode distribution does involve drastic changes in the predicted fiber bandwidth. Equation (2) is readily generalized to account for non-uniform losses and time-dependent effects. Detailed results concerning the R^2L product will be presented for various curvature spectra.

III - Experiments

The purposes of our experiments are twofold : firstly, determine what kind of desirable distortion spectrum can be realized in practice and secondly verify our theoretical expectations concerning the microbending loss, the steady-state irradiance, the bandwidth etc... We have therefore constructed a fiber-pulling machine that can be introduce controlled distortions on line (Fig.2). We have also developed a new technique for measuring these deformations.

A recently demonstrated fiber bandwidth-measurement technique⁷ requires only short fiber samples (about 0.2 meter long). Because only short samples are needed, we were not particularly concerned with the material losses, and we used for convenience ordinary glasses. But the fiber distortions have to be large enough to cause a significant increase of bandwidth (and loss) over the short length considered.

The most effective means of distorting the fiber that we found is to let the fiber pass between two gear-like wheels at it is being pulled. Comparatively high flame temperatures and small pulling forces are required. The fiber deformations are of course permanent. When the fiber is illuminated by a broad laser beam, bright, almost periodic, horizontal lines appear that are caused by reflection and focusing from the outer fiber surface. Focusing takes place at the points of maximum curvature, alternately on each side of the fiber. The focal points are clearly visible in Fig.3. We have calculated and verified that the location of these focal points is independent of the position of the screen located behind the fiber, and is precisely equal to the radius of curvature of the fiber axis. A minimum radius of curvature of 4 cm was measured. The microbending loss measured on that sample using an Argon-ion laser was as high as 90 dB/m. So far, only order-of-magnitude agreement with theory has been checked. But it appears that all experimental conditions are met to enable us to verify (or invalidate) the theory on the basis of measurements on short samples.

References

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