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Design Diagrams for Depressed Cladding Single-Mode Fibers

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Dispersion, cutoff wavelength, and mode field radius requirements place conflicting demands on the design of single-mode fibers. Using empirical models that relate these requirements to the core parameters in the preform stage, we present a single-mode design diagram for a depressed cladding fiber design showing the regions of core diameter and index difference that satisfy the requirements. The requirements with the greatest impact on fiber yield are the maximum value of the zero dispersion wavelength, the maximum value of the cutoff wavelength, and the allowable variations in the mode field radius.

I. INTRODUCTION

The optical requirements on a single-mode fiber impose conflicting demands on the fiber design. To meet dispersion, cutoff wavelength, and mode field radius requirements, the fiber core diameter and index of refraction difference must be controlled to within small variations about a nominal value, and the tightness of these specifications will directly affect the yield when making the fiber. In this paper, we examine the effects of fiber requirements on yield and identify those requirements that have the greatest impact.

This study will deal with a depressed cladding fiber design, whose index profile is shown with its nominal parameters in Fig. 1. This fiber design has been thoroughly studied. Considerable measurement data are available for this type of fiber with wide variations in fiber

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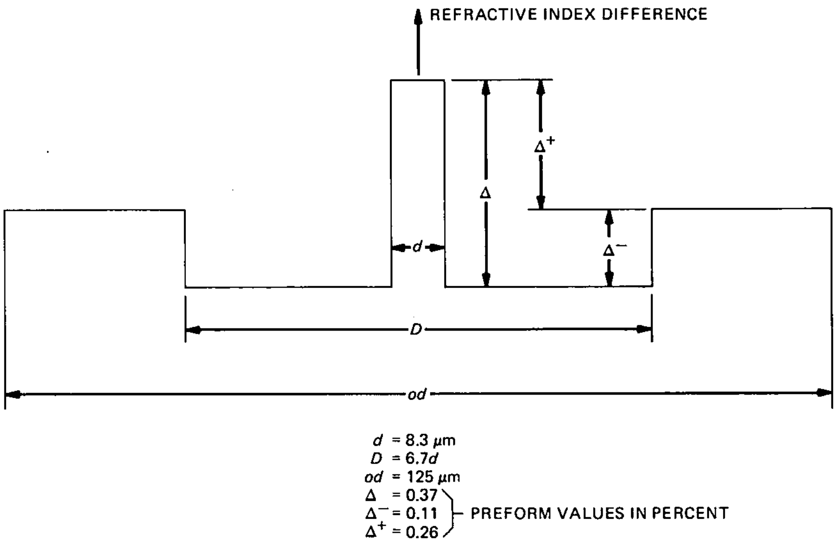

Fig. 1—Refractive index profile of a depressed cladding fiber. Nominal parameters are shown.

parameters about the nominal values except for the cladding index (Δ^-) and clad-to-core diameter ratio (D/d), which were well controlled at the nominal values shown in Fig. 1. These data have been used to develop simple empirical models that relate the core parameters (d and Δ) to the dispersion, cutoff wavelength, and mode field radius. Since the index-of-refraction profiles are more easily measured for preforms than for fibers, core dimensions scaled from their preform values were used. The index of refraction measured in the fiber will differ from that measured in the preform,[1] but as long as the preform values are used consistently, the validity of the empirical models should not be affected. Also, models based upon preform measurements are more useful for manufacturing.

In Section II we discuss the models in detail, and in Section III we present the single-mode design diagrams, which show the relationship between system requirements and fiber parameters.

II. EMPIRICAL MODELS

Chromatic dispersion, which limits the bit rate of a digital system operating on a single-mode fiber, passes through zero at a wavelength (λ_0) near 1.3 μm. Since the shape of the chromatic dispersion curve as a function of wavelength for a nearly step-index fiber is not sensitive to the fiber design parameters, specifying λ_0 is sufficient to ensure that the fiber dispersion is adequately low over the range of wavelengths that may be used in the system. The dispersion in a single-mode fiber may be predicted by numerical solutions of the field equations.[2] However, these solutions themselves give little insight into the dependence of λ_0 on core index parameters. Accordingly, a set of values encompassing the expected range of core diameters ($7 < d < 10$ μm) and index differences ($0.15\% < \Delta < 0.50\%$) were used in a program that solves the scalar wave equation numerically,[2] and the λ_0 for each combination was computed. The core parameters, d and Δ, and λ_0 were then used in a multiple linear regression program to find a simple, accurate relationship between λ_0 and d and Δ. After trying several different powers of d and Δ, the following model was selected:

$$\lambda_0 = C_0 + \frac{C_1}{d} + C_2\sqrt{\Delta}. \tag{1}$$

For example, after we compared the computed λ_0's with eq. (1), we obtained a correlation coefficient (ρ^2) of 0.996 for a family of fibers with nearly step-index Ge-doped cores and pure SiO_2 claddings ($\Delta^- = 0$, or "matched"). λ_0 was calculated for a limited number of alternative profile shapes and dopants, and the same functional form with slightly different coefficients was an excellent fit to the computed values of λ_0 in every case. This model is also appropriate for depressed cladding fibers if the cladding diameter is large relative to the core diameter (i.e., $D/d > 5$), so that the dispersion behavior is similar to that of a matched cladding fiber. To use this model empirically, a set of coefficients that characterize measured, not computed, data was found. A linear regression analysis of measured values of λ_0 for a group of depressed-cladding fibers as a function of core diameter and delta gave the following best-fit coefficients:[3]

$$C_0 = 1.207$$

$$C_1 = 1.933$$

$$C_2 = -0.2149$$

with $\rho^2 = 0.94$. If we use these coefficients, eq. (1) gives λ_0 in micrometers if d is expressed in micrometers and Δ in percent. While core diameter and delta were varied, Δ^- and D/d were held at the nominal values, shown in Fig. 1.

Cutoff wavelength can also be modeled. For an ideal step-index fiber, the theoretical cutoff wavelength is

$$\lambda_{c_{th}} = \frac{\pi d n}{2.405}\sqrt{2\Delta}, \tag{2}$$

where n is the index of refraction of the cladding. The measured cutoff wavelength, λ_c, for the standard 5-meter sample length is well characterized by the empirical relation

$$\left(\frac{\lambda_c}{d}\right)^2 = 0.861\left(\frac{\lambda_{c_{th}}}{d}\right)^2 + 0.0006 \tag{3}$$

with $\rho^2 = 0.92$. The λ's and d's are measured in micrometers. The measured cutoff wavelength is expected to be lower than the theoretical cutoff wavelength in depressed cladding designs since the higher-order mode becomes leaky and highly attenuated well below $\lambda_{c_{th}}$. Defining the normalized frequency as

$$V = \frac{\pi d n}{\lambda}\sqrt{2\Delta}$$

then eq. (3) corresponds to a cutoff V value of approximately 2.61 instead of the theoretical value of 2.405 for an ideal step-index matched-cladding fiber.

The width of the field distribution in the core of the fiber (the mode field radius, or ω_0) is important in controlling splice loss and laser launching efficiency. Since the fields are nearly Gaussian,[4] the width parameter of the Gaussian function that best fits the near field

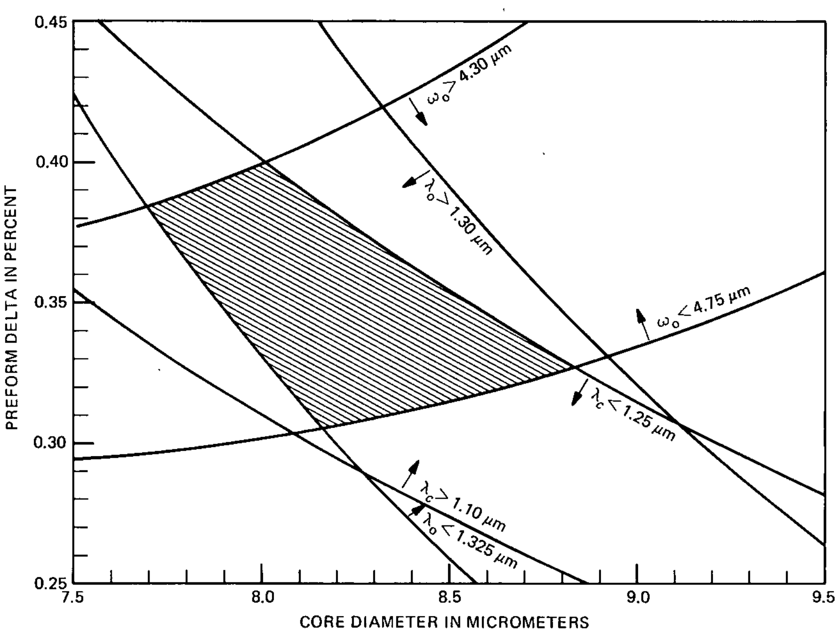

Fig. 2—Constraints imposed by tolerances on λ_0, λ_c, and ω_0. The trapezoidal region represents all combinations of d and Δ that meet the requirements placed upon λ_0, λ_c, and ω_0.

adequately characterizes the field distribution. Marcuse[5] has found the following empirical relationship:

$$2\,\frac{\omega_0}{d} = 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\,. \tag{4}$$

This empirical formula has been found to agree well with measured values.

III. SINGLE-MODE FIBER DESIGN DIAGRAMS

Consider the following system requirements as an example:

$$1.300 \leqslant \lambda_0 \leqslant 1.325\ \mu\text{m}$$

$$1.10 \leqslant \lambda_c \leqslant 1.25\ \mu\text{m}$$

$$4.30 \leqslant \omega_0 \leqslant 4.75\ \mu\text{m}.$$

Using the empirical models developed in the previous section, curves of constant λ_0, λ_c, and ω_0 corresponding to these limits are plotted as a function of d and Δ in Fig. 2. (A somewhat similar diagram for matched-cladding fibers has been published by Ainslie et al.[6]) The area inside the nearly trapezoidal shaded region represents the allow-

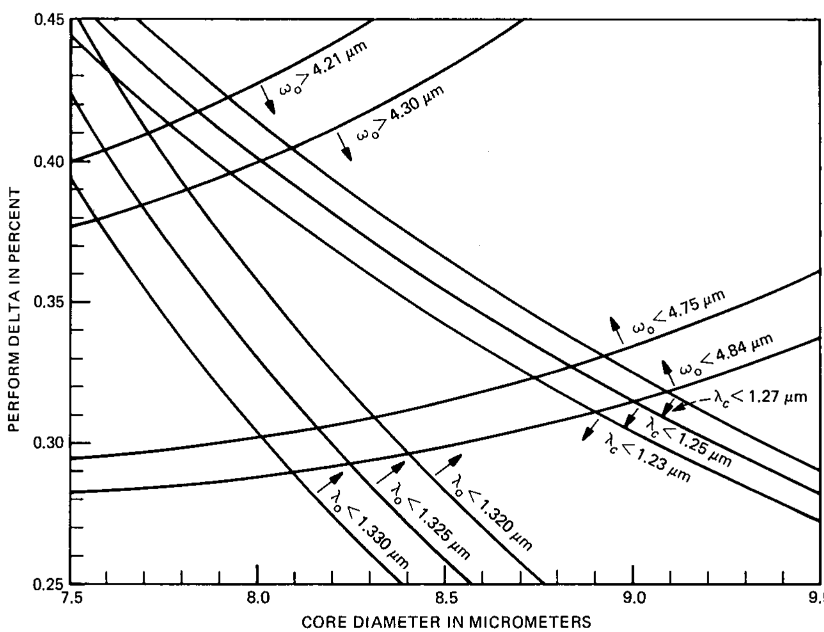

Fig. 3—Sensitivity to parameter tolerances. Changing the maximum λ_0, λ_c, or ω_0 can severely alter the size of the allowable region.

able combinations of d and Δ required to meet dispersion, cutoff, and mode field radius requirements. Several conclusions may immediately be drawn. First, only the upper limit on λ_0 will affect yield. The lower limit will not be approached if the cutoff wavelength and mode field radius requirements are met. Second, $\lambda_c > 1.10\ \mu m$ if all other requirements are met, so the minimum λ_c requirement also appears to be unnecessary. Finally, the tolerance on ω_0 (± 5 percent) does significantly reduce the size of the allowable region. The effect of the various parameter values on the size of the allowable region is shown in Fig. 3.

These diagrams also provide immediate feedback before fibers are drawn from the preforms. If a preform profile indicates that the fibers drawn from the preform will not have the desired properties, then the preform may be scrapped to avoid drawing and measuring fibers that will not be acceptable.

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