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EXCESS LOSS DUE TO THERMAL BUCKLING IN DOUBLE-COATED SINGLE-MODE OPTICAL FIBERS

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Optical fibers are always coated with a protective jacket to secure them against external forces. If the thermal expansion coefficient of the coating material is larger than that of the fiber, thermal buckling is caused by compressive force exerted on the fiber as its operating temperature decreases. Calculations have shown that there must exist other sources of compressive strain for the fiber to buckle. We study the microbending mechanism as a possible source of added losses at low temperatures and then investigate the parameters through which such a loss can be minimized.

A dual coated fiber has a soft inner primary coating to withstand the lateral stresses and an outer robust secondary layer to allow handling. A temperature drop from T_o to T_f will cause a thermal strain, ε_t, that is related to the fiber thermal expansion coefficient, α_f, by

$$\varepsilon_t = \int_{T_o}^{T_f} (\alpha_{eff} - \alpha_f) \, dT \quad , \tag{1}$$

where α_{eff} is the effective thermal expansion coefficient of the coated fiber defined through

$$\alpha_{eff} = \frac{\sum_i \alpha_i A_i E_i}{\sum_i A_i E_i} \quad , \tag{2}$$

as A_i and E_i are the cross sectional area and the modulus of elasticity of the i^{th} constituent material, respectively.

An equilibrium equation for the forces in the optical fiber at low temperatures is given in terms of y, the optical fiber deformation generated by the jacket compressive force, F, as

$$E_f I \frac{d^4 y}{dz^4} + F \frac{d^2 y}{dz^2} + \kappa y = 0. \quad , \tag{3}$$

where the subscript f denotes the fiber and κ is the spring constant defined by the following equation [1]

$$\kappa = \frac{4 \pi E_p (1 - \sigma_p) (3 - 4 \sigma_p)}{(1 + \sigma_p) \left[(3 - 4 \sigma_p)^2 \ln \left(\frac{r_p}{r_f} \right) - \frac{r_p^2 - r_f^2}{r_p^2 + r_f^2} \right]} \quad , \tag{4}$$

with σ the Poisson ratio, r the radius, and the subscript p stands for the primary layer. Assuming the deformation to have the form

$$y = C \sin\left(\frac{2\pi z}{P}\right) \quad , \tag{5}$$

where C is a constant that is proportional to the temperature, z is the axial distance, and P is the wave pitch, one can get the minimum force to cause buckling from Eq. (3). This force has been found to be

$$F_{min} = r_f^2 (\pi E_f \kappa)^{\frac{1}{2}} \quad , \tag{6}$$

and it corresponds to a minimum mechanical compressive strain of

$$\varepsilon_m = \left(\frac{\kappa}{\pi E_f}\right)^{\frac{1}{2}} \quad , \tag{7}$$

When the fiber buckles it acquires a certain curvature that is described by a fiber bending radius, ρ_b, that is determined from

$$\rho_b = \frac{r_f}{2}\left(\frac{\pi E_f}{\varepsilon_d^2 \kappa}\right)^{\frac{1}{2}} \quad , \tag{8}$$

where ε_d is the strain difference between the fiber and the coating and it is defined with the aid of Eqs. (1) and (7)

$$\varepsilon_d = \varepsilon_m - \varepsilon_t \quad , \tag{9}$$

For single mode fibers, the bending loss, α, per unit of length of the fiber is given by the following formula [2] using the value of curvature found with Eq. (8)

$$\alpha = \frac{\sqrt{\pi}\, k^2 \exp\left[-\frac{2}{3} \rho_b \left(\gamma^3 / \beta^2 \right) \right]}{2 \gamma^{\frac{3}{2}} V^2 \rho_b^{\frac{1}{2}} K_{-1}(\gamma r_c) K_1(\gamma r_c)} , \qquad (10)$$

where β is the propagation constant, V is the normalized frequency, k and γ are the transverse propagation constants for core and cladding, respectively, and $K_n(x)$ is the modified Bessel function of n^{th} order. The subscript c marks out the core.

The normalized frequency and the propagation constants may be found for the type of fiber under investigation; that is the biquadratic - index type. Equations (8) and (10) explain how the physical parameters of the fiber can affect the transmitted power through a dual-coated fiber. The fiber under examination is chosen to be made of silica, primary and secondary layers are, respectively, made from silicon and nylon. A general result that proves the microbending role in the additional loss is that with the decrease of ρ_b; or the increase of deformation; additional loss increases. However, not all the studied parameters has the same effect. Figuers 1,2,and 3 show the effect of the fiber,primary, and secondary radii, respectively, on both ρ_b and α. Those results prove the importance of suitable selection of the layers thicknesses. The fiber's outer diameter has to be relatively thin while the primary and secondary layers have to be substantially thicker with a special importance for the primary one. These results are in good agreement with the simple bending model and with the previously reported results [3].

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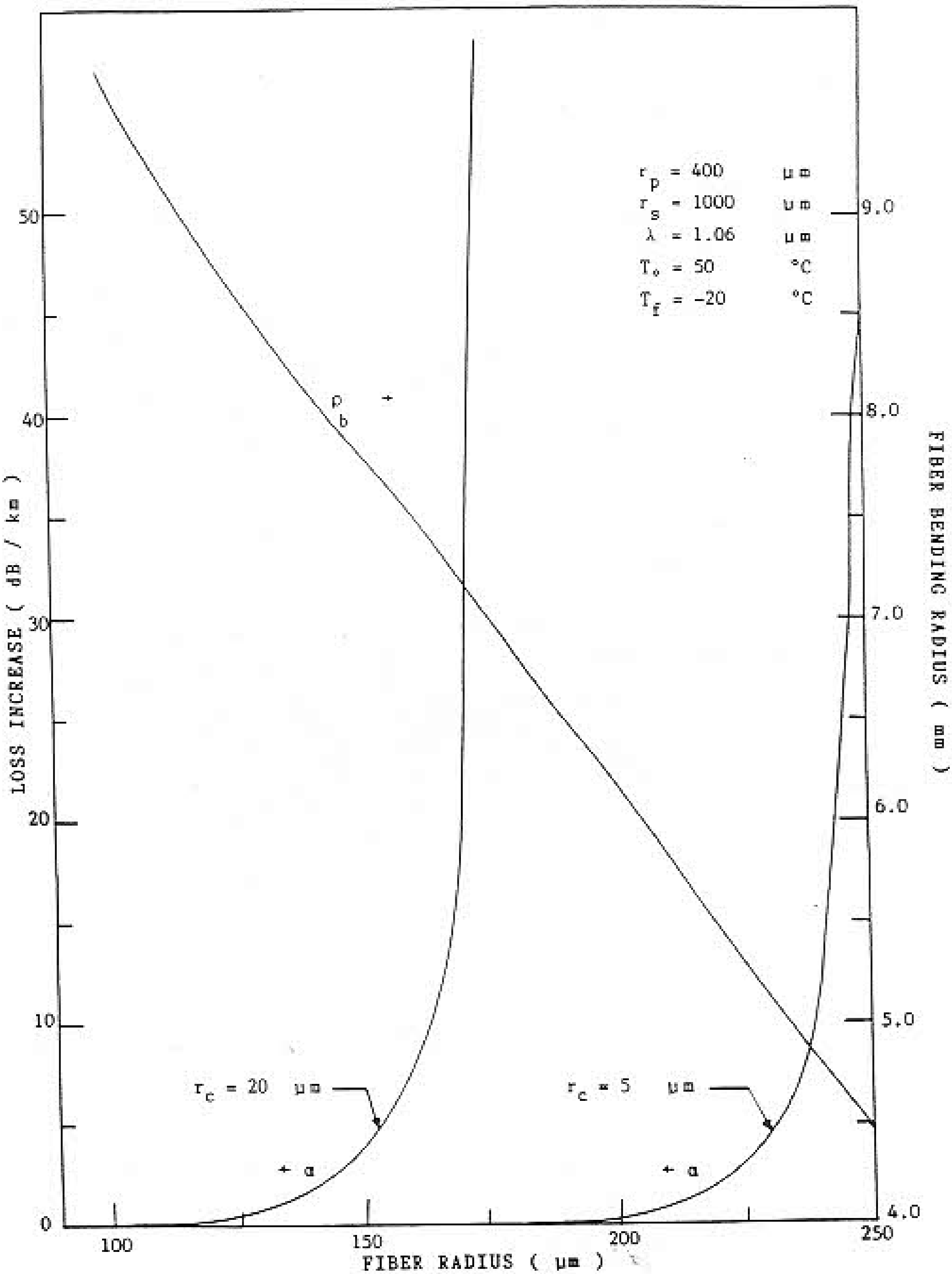

Fig.1 Effect of r_f on both α and ρ_b

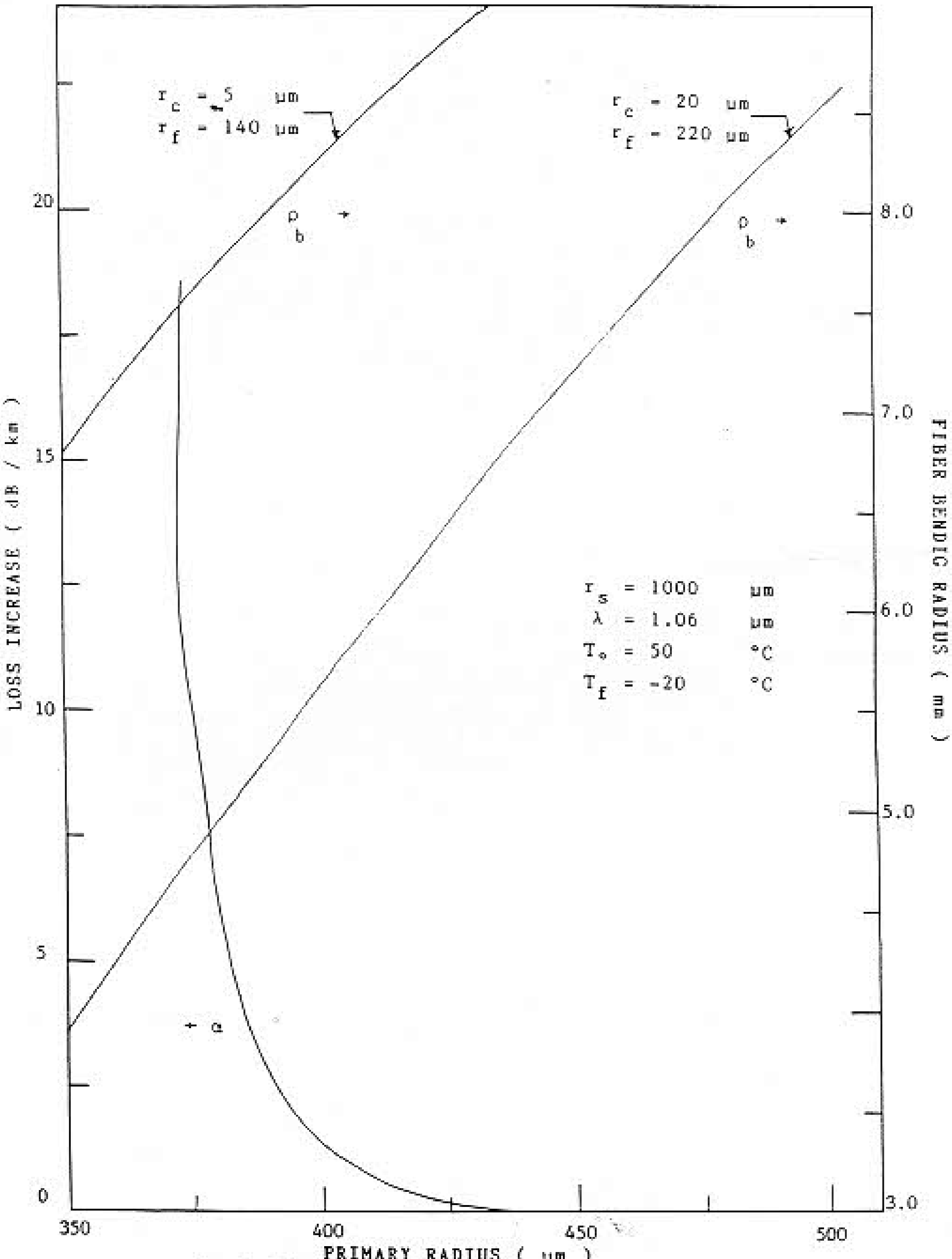

Fig.2 Effect of r_p on both α and ρ_b

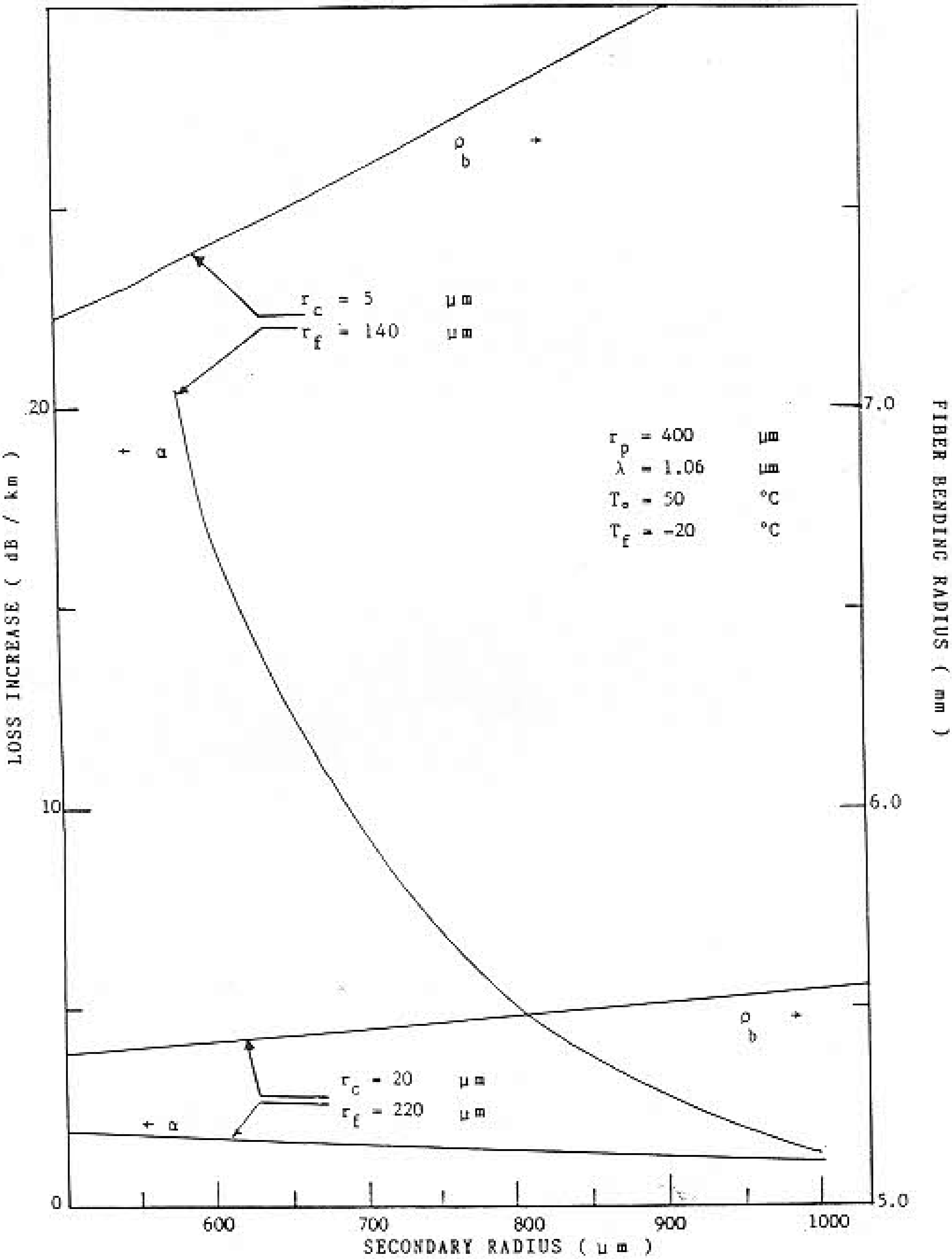

Fig.3 Effect of r_s on both α and ρ_b

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CONTENTS

AUTHOR INDEX

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EXCESS LOSS DUE TO THERMAL BUCKLING IN DOUBLE - COATED SINGLE - MODE OPTICAL FIBERS

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ABSTRACT

Double coated fibers display additional transmission loss due to microbending of the fiber axis at low temperatures. A proper design of the fiber and its coating can control the fiber deformation and suppress excess losses.

INTRODUCTION

Optical fibers need protection from external forces and this requires the design of a protective fiber jacket. The jacket should have a high stiffness in combination with a good lateral compressibility. Had the thermal expansion coefficient of the coating material been considerably larger than that of the fiber, buckling is caused by compressive stress exerted on the fiber when its operating temperature decreases. This type of deformation is known as thermal buckling.

Calculated results have indicated that thermal strain falls short of the mechanical strain, which is the minimum compressive strain that can cause the fiber to buckle. Other sources of strain were suggested including the microbending mechanism [1]. Microbending is a series of random bends in the fiber axis that may be induced by either increasing lateral pressure on the fiber or by thermal buckling.

An approach to minimize microbending losses is to select proper coating materials according to their respective mechanical properties. The main parameters that govern our choice are the material's modulus of elasticity and thermal expansion coefficient.

The following study presents a theoretical treatment for the micro-

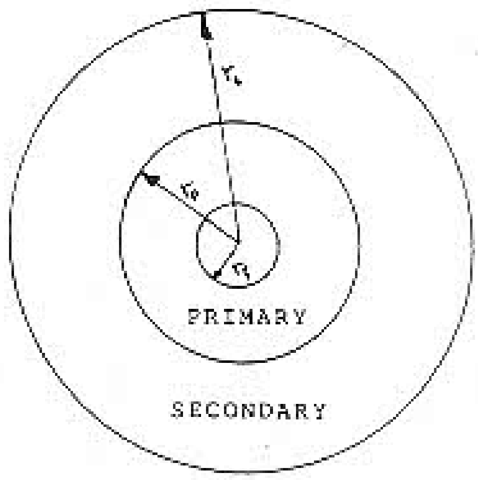

Fig.1. Double - coated optical fiber .

bending problem of a biquadratic - index dual - coated fiber. Dual coatings are introduced to reduce the effects of lateral pressure by buffering the fiber with a soft inner primary layer; the outer secondary layer is hard and robust to allow handling .

THERMAL BUCKLING

A dual - coated fiber, Fig. 1, has a primary coating layer that is chosen from a suitable material, e.g. silicon , to minimize lateral pressures, while the secondary layer has a mainly protective function against handling problems .

The different thermal expansion coefficients of the fiber and its coatings can be consolidated into an effective expansion coefficient, α_{eff}, defined by the rule of mixtures [2] as :

$$\alpha_{eff} = \frac{\sum_i \alpha_i A_i E_i}{\sum_i A_i E_i} \quad , \tag{1}$$

where α_i denotes the thermal expansion coefficient , A_i is the cross-sectional area and E_i is the Young's modulus of elasticity of the i^{th} material .

The thermal strain ε_t is related to the temperature change from T_o, a standard temperature, to a final temperature, T_f, by :

$$\varepsilon_t = \int_{T_o}^{T_1} (\alpha_{eff} - \alpha_f)\, dT \quad , \tag{2}$$

where α_f denotes the thermal expansion coefficient of the fiber . Since the Young's modulii of the coating materials are known to depend on temperature, the integration of Eq. 2 is to be performed numerically once the temperature dependence is clarified.

MECHANICAL BUCKLING

The fiber may buckle because of a compressive strain and thus it follows a helical path. Using the theory of elastic stability, a force and moment balance yields the differential equation [3] :

$$E_f I \frac{d^4 y}{dz^4} + F \frac{d^2 y}{dz^2} + \kappa y = 0 \quad , \qquad (3)$$

where y is the deflection of the fiber as a function of the distance z along its length. The parameters E_f , I , and F are, respectively, the Young's modulus of the fiber, the geometrical moment of inertia of the fiber and the compressive force on the fiber. The spring constant κ is defined as the centring force exerted by the coating to the displacement of the fiber from the center. It is determined from [4] :

$$\kappa = \frac{4\pi E_p (1-\nu_p)(3-4\nu_p)}{(1+\nu_p)\left[(3-4\nu_p)^2 \ln\left(\frac{r_p}{r_f}\right) - \frac{r_p^2 - r_f^2}{r_p^2 + r_f^2} \right]} \quad , \qquad (4)$$

where r_f is the radius of the fiber, r_p, E_p and ν_p are, respectively, the primary radius, Young's modulus and Poisson's ratio.

The buckling solution of Eq. 3 has the form :

$$y = C \sin\left(\frac{2\pi z}{P}\right) \quad , \qquad (5)$$

where C is an arbitrary constant that is directly proportional to the temperature, and P is the helical's pitch. Back substitution to Eq. 3 gives :

$$F = E_f I \left(\frac{2\pi}{P}\right)^2 + \kappa \left(\frac{P}{2\pi}\right)^2 \quad , \qquad (6)$$

from which one can get the minimum buckling force as :

$$F_{min} = 2 (I E_f \kappa)^{\frac{1}{2}} = r_f^2 (\pi E_f \kappa)^{\frac{1}{2}} \quad . \qquad (7)$$

This corresponds to a minimum pitch of :

$$P_{min} = \pi r_f \left(\frac{4\pi E_f}{\kappa}\right)^{\frac{1}{4}} \quad , \qquad (8)$$

and a minimum mechanical compressive strain :

$$\varepsilon_m = \left(\frac{\kappa}{\pi E_f}\right)^{\frac{1}{2}} \quad . \qquad (9)$$

Again one may notice that through the dependence of κ on E_p, the mechanical strain, ε_t , is a function of temperature.

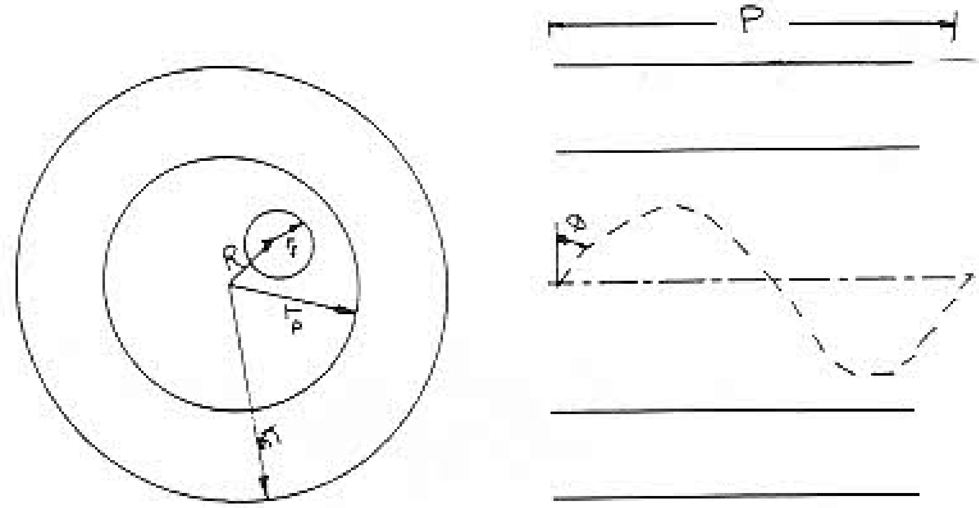

Fig.2. fiber bending model to evaluate loss increase .

FIBER BENDING RADIUS

Figure 2 represents a simple model of fiber bends when it exhibits a temperature drop. It is assumed that the fiber bends due to the cooling contraction difference between the primary coating and the fiber . When a spiral bend occurs, the bending radius ρ_b is given by :

$$\rho_b = \frac{R}{\cos^2 \phi} \quad , \qquad (10)$$

where R is the spiral radius and ϕ is the angle between the fiber and the line normal to the central axis .

When the fiber buckls, the strain difference, ε_d, between the fiber and the coating is related to ϕ by :

$$\varepsilon_d = \varepsilon_m - \varepsilon_t = \frac{1}{2}\cos^2 \phi \quad . \qquad (11)$$

Since ϕ is almost a right angle, the following approximation holds :

$$\tan \phi = \frac{P}{2 \pi R} \quad , \qquad (12)$$

and the radius R is related to the spiral pitch P by :

$$R = \frac{P}{2 \pi} (2 \varepsilon_d)^{\frac{1}{2}} \quad . \qquad (13)$$

Using Eqs. 8, 11 and 12 in Eq. 10, one can get :

$$\rho_b = \frac{r_f}{2} \left(\frac{\pi E_f}{\varepsilon_d^2 K} \right)^{\frac{1}{2}} \quad . \qquad (14)$$

LOSS INCREASE AT LOW TEMPERATURE

For single mode fibers, only the fundamental LP_{01} mode is propagating within the fiber. Therefore, the loss coefficient α_{01} for this mode is given by [5] :

$$\alpha_{01} = \frac{\sqrt{\pi}\,\zeta^2 \exp(-2\rho_b \gamma^3 / 3\beta^2)}{2\gamma^{3/2} V^2 \sqrt{\rho_b}\, K_{-1}(\gamma r_c) K_{+1}(\gamma r_c)} \quad , \tag{15}$$

where β is the axial propagation constant, γ and ζ are, respectively, the transverse propagation constants in the core and cladding, $K_{\pm 1}(z)$ are the modified Bessel functions, V is the normalized frequency and r_c is the core radius.

It is concluded that the fiber bending model and the curvature loss formula, Eq. 15, can represent the loss increase characteristics of a dual - coated single - mode fiber due to cooling.

RESULTS AND DISCUSSION

Equations 14 and 15 explain how the physical parameters of the fiber can affect the transmitted power through a dual - coated fiber. The fiber under examination is chosen to be made of silica with primary and secondary coatings which are made, respectively, of silicon and nylon layers.

As mentioned before, the modulii of elasticity of the coatings change drastically over the range of operating temperatures. We have obtained their values for a wide range of temperatures from the published experimental data [6]. The best fitting formulae for these results were found to be :

$$E_p(T) = 1.014 - 0.02\,T \quad , \tag{16}$$

and

$$E_s(T) = 1216 - 9.77\,T + 0.03\,T^2 + 0.017\,T^3 - 4.9\times 10^{-4}\,T^4 - 2.5\times 10^{-5}\,T^5 + 4.3\times 10^{-7}\,T^6 + 8.9\times 10^{-9}\,T^7 - 1.4\times 10^{-10}\,T^8 \quad , \tag{17}$$

where E_s is the young's modulus of the secondary layer. When T is given in °C, $E_p(T)$ and $E_s(T)$ will result in megapascals. Equations 16 and 17 are used in Eq. 2 and a computer program has been designed to execute all the numerical calculations. The main object is to find the optimum parameters that will result in minimum loss increase due to any temperature drop.

We have studied a biquadratic - index profile defined by :

$$n(\rho) = n_0 (1 - 2\alpha\rho^2 + 2m\alpha\rho^4)^{\frac{1}{2}} \quad , \tag{18}$$

where n_0 is the axial refractive index and α and m are two controlling parameters. Through this profile we have defined the propagation constants needed for Eq. 15. The axial propagation constant β is calculated by the perturbation theory to the third order as [7] :

$$\beta^2 = k_0^2 - \frac{2k_0\sqrt{2\alpha}}{r_c} + \frac{2m}{r_c^2} + \frac{9\,m^2}{2r_c^3 k_0 (2\alpha)^{\frac{1}{2}}} + \frac{79\,m^3}{8\alpha (r_c^2 k_0)^2} \quad , \tag{19}$$

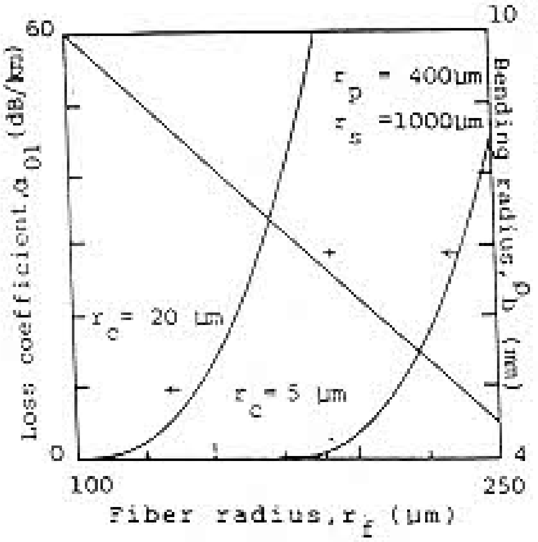

Fig.3. Effect of r_f on α_{01} and ρ_b

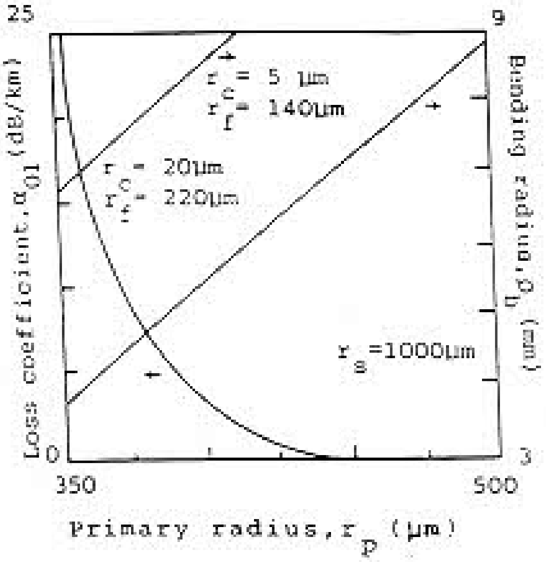

Fig.4. Effect of r_p on α_{01} and ρ_b

where k_o is the free space propagation constant .

The effect of the different radii of the fiber's layers have been investigated. A general result that proves the microbending role in the additional losses is that with the decrease of ρ_b , or the increase of the deformation, the loss coefficient α_{01} always increases.

The importance of suitable selection of r_f, r_p and r_s is well observed from Figs.3 - 5. Figure 6 depicts a reported experimental result [8] which regarded a relatively thick secondary coating as an adequate precaution to avoid fiber buckling.

CONCLUSIONS

From the foregoing results, we can draw the following conclusions :

1. The selection of the coating materials has to be made according to their functions. The primary layer must be made of a soft material, such as silicon, to imprint irregularities in the fiber axis, while the secondary layer must be hard , such as nylon , to withstand external forces.
2. To reduce the microbending loss , one has to choose the fiber radius r_f < 200 μm, the primary radius r_p > 400 μm and the secondary radius r_s > 800 μm, Figs.3-5. Thinner fibers and thicker coatings are preferable .
3. The bending curvature radius ρ_b is directly related to the microbending excess - loss. Smaller values of the bending radius means more additional losses .

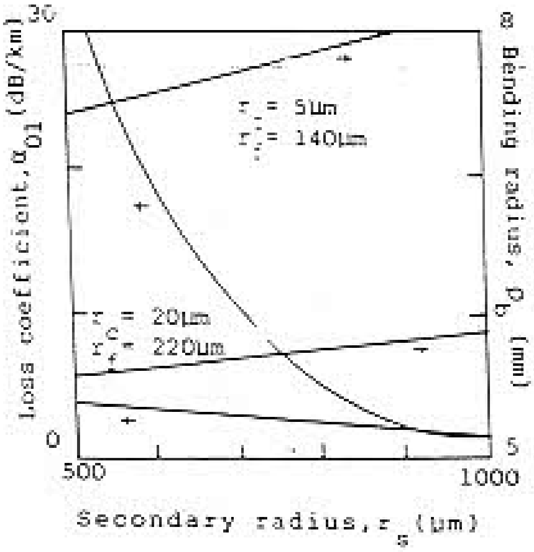

Fig.5. Effect of r_s on α_{01} and ρ_b

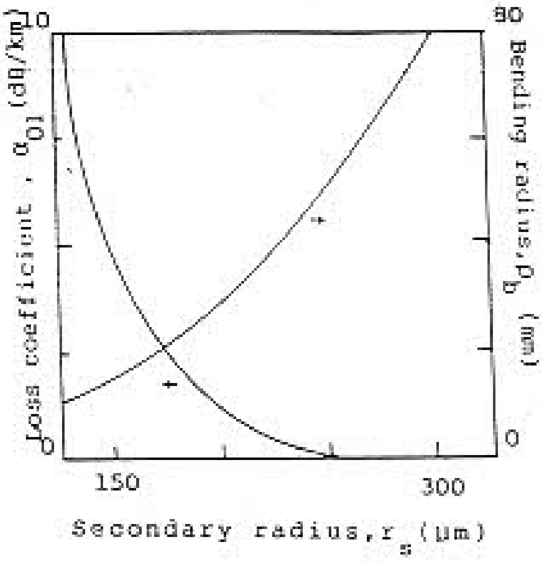

Fig.6. Experimental results [8] for the effect of r_f on α_{01} & ρ_b

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