THERMAL MICROBENDING IN GRADED-INDEX MULTIMODE OPTICAL FIBERS

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ABSTRACT

Optical fibers exhibit losses due to thermal microbending that occurs to the fiber axis during any significant temperature drop. Thermal microbending loss coefficient is found to depend on the fiber parameters as well as the number of propagating modes.

INTRODUCTION

Multimode optical fibers are still important for special applications such as local area networks. Research and development on these fibers is now devoted to decreasing operational losses exhibited by the fiber during optical power transmission. Of these mechanisms, is the microbending loss [1,2] and the thermal microbending loss which results from any significant drop in the operating temperature.

For stable performance, optical fibers are coated to be protected from external influences. However, the coatings may have different thermal expansion coefficients than the fiber core. These differences yield unlikely length contractions and, consequently, a series of random bends along the fiber axis.

Thermal microbending is calculated through a loss coefficient which is a function of both the fiber parameters and the operating conditions. We have shown, in an earlier work [3], how to control the value of this coefficient for single-mode optical fibers. The object of the present work is to generalize the previous work for the multimode type of fibers. We present an analytic study to indicate how the parameters affecting the thermal microbending coefficient can be compromized in the case of graded index multimode optical fibers.

MODEL AND ANALYSIS

Under the compressive forces at low temperature, optical fibers suffer a buckling deformation. However, fibers will not buckle unless the cooling strain exceeds the mechanical limit set by the Young's modulus of elasticity.

A- Cooling Strain

Using the rule of mixtures, the different thermal expansion coefficients of the fiber coatings can be lumped together into an effective expansion coefficient, α_e, under the form [4]:

$$\alpha_e = \frac{\sum_i \alpha_i A_i E_i}{\sum_i A_i E_i} \tag{1}$$

where α_i, A_i and E_i are, respectively, the thermal expansion coefficient, cross-sectional area and Young's modulus of elasticity of the i<u>th</u> coating layer.

Due to the thermal expansion coefficients difference, a drop in the temperature by an amount ΔT, results in an axial contraction strain, ε_t, which is defined by:

$$\varepsilon t = \int_{\Delta T} (\alpha_e - \alpha_f)\, dT, \tag{2}$$

where α_f denotes the fiber thermal expansion coefficient. In general, α_e is temperature dependent through the dependence of Young's modulii on temperature. This dependence must be cleared to perform the integration of equation (2) numerically.

B- Loss Increase Due to Buckling

In the case under investigation, a compressive force, F, occurs during the temperature drop. To explain the loss increase, a bending model related to the buckling effect was proposed [5]. In this model, it is assumed that the buckling deformation follows a helical path to which the fiber bending radius is related by:

$$\rho_b = \frac{R}{\cos^2\phi} \simeq \frac{R}{2\varepsilon_d}, \quad (3)$$

where R is the spiral radius, ϕ is the angle between the fiber and the normal to the central axis and ε_d is the strain difference represented by:

$$\varepsilon_d = \varepsilon_t - \varepsilon_m, \quad (4)$$

where ε_m is the mechanical strain.

Applying the theory of elastic stability, the equilibrium equation for the forces at low temperature is given by [6]:

$$E_f I \frac{d^4 y}{dz^4} + F \frac{d^2 y}{dz^2} + \kappa y = 0, \quad (5)$$

where E_f is the fiber Young's modulus of elasticity, I is the geometrical moment of inertia and κ is the spring constant determined, under the assumption that other coatings rather than the primary are rigid, from [7]:

$$\kappa = \frac{4\pi E_p (1-\nu_p)(3-4\nu_p)}{(1+\nu_p)[(3-4\nu_p)^2 \ln(\frac{r_p}{r_f}) - \frac{r_p^2 - r_f^2}{r_p^2 + r_f^2}]}, \quad (6)$$

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

The periodical solution that satisfies the buckling conditions can be written as:

$$y = y_{max} \sin(\frac{2\pi z}{P}), \quad (7)$$

where P is the spiral pitch. When the solution is submitted to equation (5), one can get the following expression for the minimum force, F_{min}, that can result in a buckling to the fiber axis:

$$F_{min} = r_f^2 \sqrt{\pi E_f \kappa}\,, \quad (8)$$

to which the corresponding spiral pitch is:

$$P_{min} = \pi r_f (\frac{4\pi E_f}{\kappa})^{1/4}. \quad (9)$$

But, the fiber bending radius, ρ_b, is related to the spiral pitch, P, by the relation:

$$\rho_b = \frac{P}{2\pi\sqrt{2\,\varepsilon_d}}. \quad (10)$$

Therefore, using equation (10), the bending radius, ρ_b, can be rewritten as:

$$\rho_b = \frac{r_f}{2}(\frac{\pi E_f}{\varepsilon_d^2 \kappa})^{1/4}. \quad (11)$$

The obtained thermal deformation is used to estimate the thermal microbending loss coefficient through the Marcuse formula [8]:

$$\alpha_m = \frac{\sqrt{\pi}\,\zeta^2 \exp(-2\rho_b \gamma^3/3\beta^2)}{e_\nu \gamma^{1.5} V^2 \sqrt{\rho_b} K_{m-1}(\gamma r_c) K_{m+1}(\gamma r_c)}, \quad (12)$$

where β is the axial propagation constant, ζ and γ are, respectively, the transverse propagation constants of the core and the cladding, V is the normalized frequency, r_c is the core radius and $K_l(x)$ is the modified Bessel function of the l<u>th</u> order, with:

$$e_\nu = 2,\ m = 0 \qquad e_\nu = 1,\ m \neq 0$$

The suffix m stands for the modal number. Hence, equation (12) calculates the respective loss for each mode. All losses for different modes are then added to each other to give α_M, the overall microbending loss coefficient:

$$\alpha_M = \sum_{m=1}^{M} \alpha_m. \quad (13)$$

C- Analysis of Biquadratic-Index Fibers

Thermal microbending loss coefficient of an optical fiber, operating at a certain wavelength λ, is controlled by its refractive index profile and its propagation constants. Practically, for a biqudratic-index profile, the core refractive index is defined through two tailoring parameters, A and B, by:

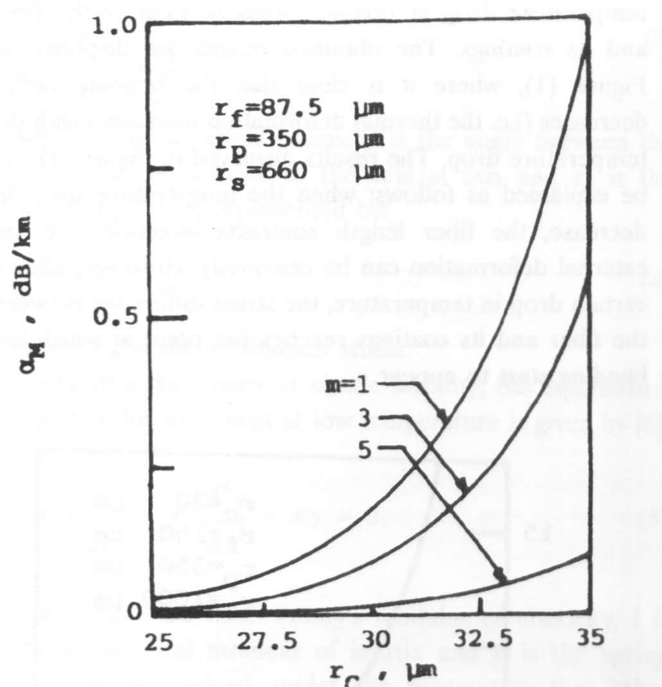

Figure 2. Variation of the microbending loss coefficient, α_m, for a propagating mode, m,with the core radius, r_c.

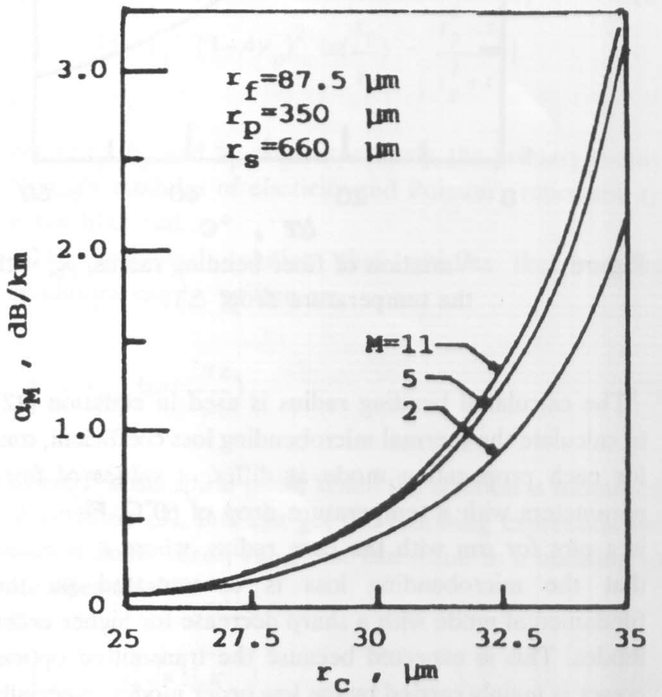

Figure 3. Variation of the overall microbending loss coefficient, α_M, with the core radius, r_c. (Effect of number of modes, M).

The effect of the total number of the propagating modes, M, on the microbending loss is given in Figure (3), where it is clear that a negligible loss is added to the overall loss for M > 6.

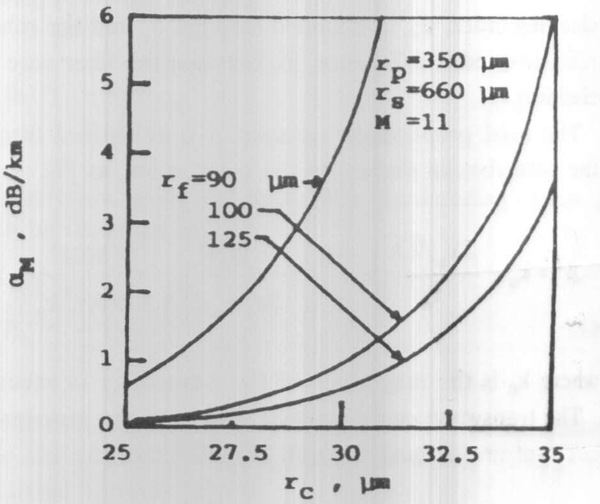

Figure 4. Variation of the overall microbending loss coefficient, α_M, with the core radius, r_c. (Effect of fiber radius, r_f).

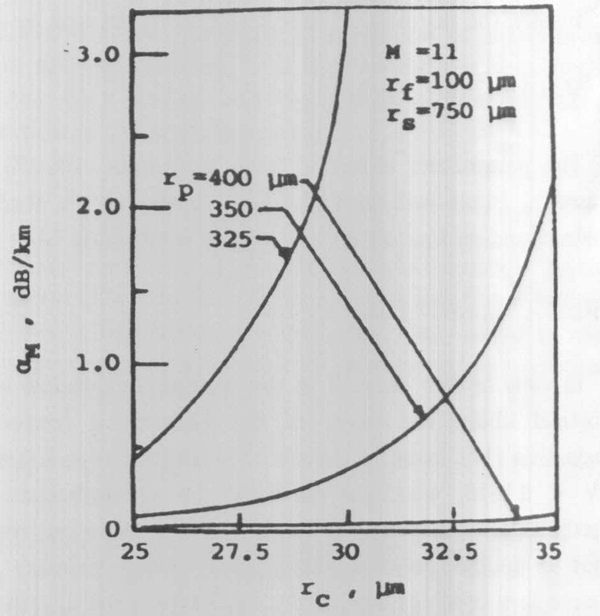

Figure 5. Variation of the overall microbending loss coefficient, α_M, with the core radius, r_c. (Effect of primary coating radius, r_p).

Figures (4, 5 and 6) confirm the importance of the appropriate design of multimode optical fibers. The core radius and the primary and secondary coatings radii must be chosen to maintain the overall microbending loss as low as possible. To achieve this, thinner fibers and thicker coatings are recommended.

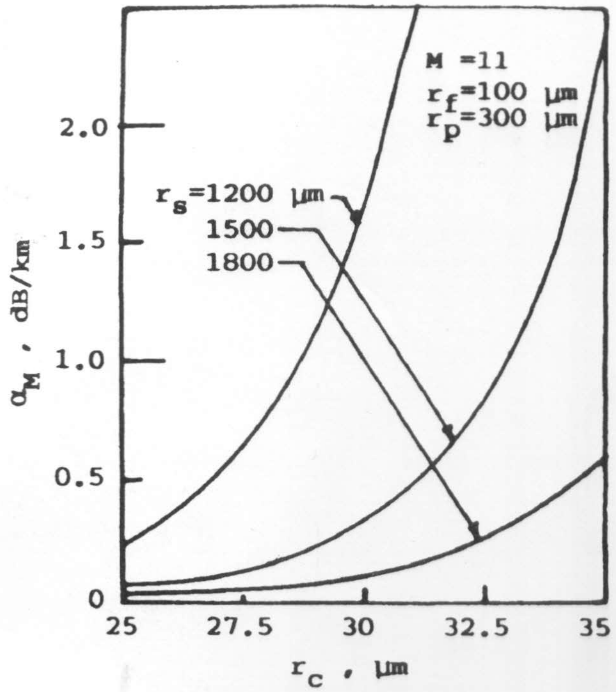

Figure 6. Variation of the overall microbending loss coefficient, α_M, with the core radius, r_c. (Effect of secondary coating radius, r_s).

CONCLUSION

Thermal microbending loss was studied for multimode biquadratic-index optical fibers. It was shown that the thermal deformation, and hence the microbending loss, increase with the temperature drop. Geometrical dimensions of the fiber and its coatings have to be adjusted, using the obtained curves, to maintain the mircobending loss within the permissible level.

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