Thermal Effects in Optical Fibers

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Abstract

Both periodic axial caustic zones and maximum axial temperature in W-tailored refractive index fibers are investigated. To reduce their harmful effects, suitable values are assigned to the parameters: the injected power, the launch conditions, the fiber core radius, and the attenuation coefficient.

Keywords: Optical Fibers. Thermal Effects. W-Tailored Refractive Index Fibers.

MODEL AND ANALYSIS

Two thermal effects in W-tailored refractive index fibers are investigated: the periodic axial caustic zones and the maximum axial temperature. The independent variables form the elements of the set (the injected power, I_o, the launch conditions, the fiber core radius, a, the tailoring parameters α and m of the refractive index, and the attenuation coefficient of the fiber, σ).

The normalized radial position, ρ (= r/a) as a function of the normalized propagation distance, η (= z/a), the fiber parameters, and the launch conditions are the solution of the Eq. [1]:

$$\frac{\partial^2 \rho}{\partial \eta^2} = \frac{1}{2n_o^2 N_o^2} \frac{\partial n^2}{\partial \rho}, \qquad (1)$$

where r is the radial distance, z is the propagation distance, N_o is the direction cosine of the incident ray, and n is the refractive index profile of the fiber core, which is defined (for the W-tailored type) as:

$$n^2(\rho) = n_o^2(1 - 2\alpha\rho^2 + 2m\alpha\rho^4). \qquad (2)$$

The use of

$$\rho_n = \rho\sqrt{2m}, \qquad (3\text{-a})$$

and

$$\eta_n = \eta/N_o \sqrt{2\alpha}, \qquad (3\text{-b})$$

in Eq.(1) yields:

$$\frac{\partial^2 \rho_n}{\partial \eta_n^2} + \rho_n - \rho_n^3 = 0, \qquad (4)$$

which is solved under the series form:

$$\rho_n = \sum_{i=0}^{\infty} C_i \, \eta_n^i, \qquad (5)$$

with the launch conditions (at $\eta = 0$):

$$\rho_o = \rho_n\big|_{z=0} = C_o = (r_o / a)\sqrt{2m}, \qquad (6)$$

and

$$\rho_o^{'} = \frac{d\rho_n}{d\eta_n}\Big|_{z=0} = C_1 = \frac{dr}{dz}\Big|_{z=0} \; N_o \sqrt{m/\alpha} \,. \qquad (7)$$

The series solution is truncated at i = 22 to a very high accuracy.

The maximum axial temperature, T_{max}, is found by solving the energy balance equation [2]:

$$\nabla_\rho^2 T_n = \frac{-\sigma I_o a^2}{T_o K}\left(\frac{\rho_o}{\rho}\right)^2 \exp\left(\frac{-2\sigma R N_o n_o \eta}{F_a^2}\right) \exp\left(\frac{-\rho^2}{F_a^2}\right) \qquad (8)$$

where $T_n = T/T_o$, T_o is the ambient temperature, K is the thermal conductivity, and F_a is the average hot spot parameter, given by:

$$F_a = \frac{1}{\rho}\int_0^\rho F(\rho\,,\eta)\, d\rho \,, \qquad (9)$$

where $F(\rho\,,\eta)$ is the hot spot parameter defined as:

$$I(\rho\,,\eta) = I_o F(\rho\,,\eta)\,. \qquad (10)$$

At the hot path-cold region interface, the heat transferred by conduction is equal to the heat transferred by convection outward, and so:

$$\frac{K}{a}\frac{dT_n}{d\rho} = H(T_n - 1)\,, \qquad (11)$$

where H is the convection heat transfer coefficient.

The use of Eqs. (9-11) in Eq. (8) yields:

$$T_{max} = T_o + 0.5\, B_o (0.5\rho^2 + \rho K/Ha)\,, \qquad (12)$$

where

$$B_o = \frac{\sigma I_o a^2}{K}\left(\frac{\rho_o}{\rho}\right)^2 \exp(-2\sigma a N_o n_o \eta)\,. \qquad (13)$$

RESULTS AND DISCUSSION

The obtained values of ρ_n, Eq. (5), are used to determine the hot spots corresponding to points of minimum ρ_n. Since periodic variation is obtained, the distance 'WAV' between two adjacent hot spots is twice the distance between two successive maximum and minimum.

The variation of the distance 'WAV' with the parameter α at different values of the parameter m is displayed in Fig. 1. The effects of the launch conditions, ρ_o and ρ_o', on 'WAV' are studied separately and similar curves are obtained.

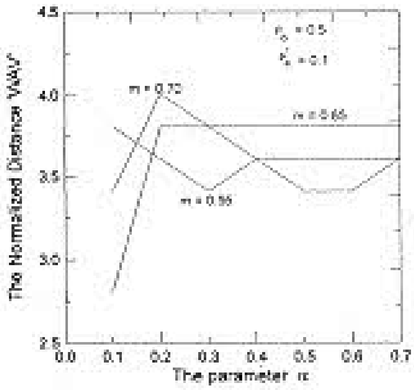

Fig. 1 Variations of the normalized distance 'WAV' with the parameter α.

The maximum axial temperature, T_{max}, is calculated through Eqs. (12) and (11) with the aid of the values of ρ_n obtained from Eq. (5). The variation of T_{max} with α is shown in Fig. 2 for constant values of m. The same range of values of T_{max} is obtained when varying ρ_o or ρ_o'.

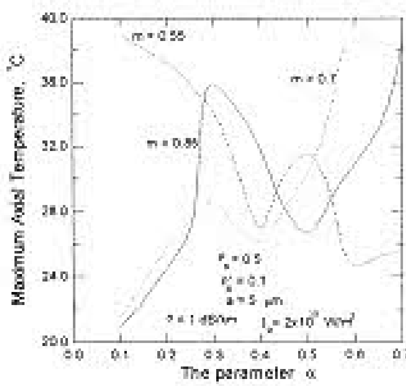

Fig. 2 Variations of the maximum axial temperature with the parameter α

Figure 3 represents the variation of T_{max} with the parameters: a, I_o, and σ at constant values of the other parameters. From Fig. 3, three linear relations between T_{max} and each of a, I_o, and σ are deduced; namely:

$$T_{max} = T_o + S_1\, a\,, \qquad (14)$$

$$T_{max} = T_o + S_2 I_o\,, \qquad (15)$$

and

$$T_{max} = T_o + S_3 \sigma, \qquad (16)$$

where the slopes S_1, S_2, and S_3 can be directly obtained from Fig. 3.

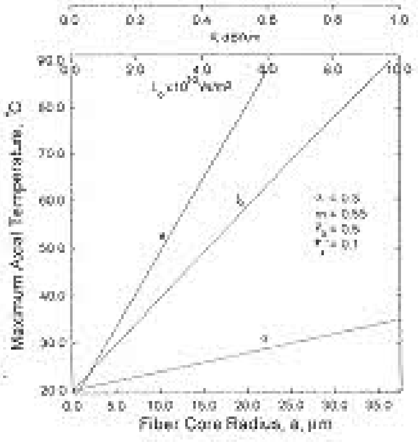

Fig.3 Variations of the maximum axial temperature with each of the core radius, a, the injected power, I_o, and the attenuation constant, σ.

Based on Ref. [3], the maximum allowable temperature is $T_{max} \leq 60$ °C. To achieve this, the obtained results indicate, at $\rho_o = 0.5$ and $\rho_o' = 0.1$ that:

For $\alpha = 0.3$ and $m = 0.55$, the core radius, a, must be $\leq$ 12.5 μm, the laser intensity, $I_o \leq 5.5\times10^{10}$ W/m^2 for values $\sigma \leq 1$ dB/km.

CONCLUSION

Two thermal effects in W-tailored refractive index fibers are investigated: the periodic axial caustic zones and the maximum axial temperature. The independent variables form the elements of the set (the injected power, I_o, the launch conditions, the fiber core radius, a, the tailoring parameters α and m of the refractive index, and the attenuation coefficient of the fiber, σ).

To achieve $T_{max} \leq 60$ °C , the obtained results indicate, at $\rho_o = 0.5$ and $\rho_o' = 0.1$ that: for $\alpha = 0.3$ and $m = 0.55$, the core radius, a, must be $\leq$ 12.5 μm, the laser intensity, $I_o \leq 5.5\times10^{10}$ W/m^2 for values $\sigma \leq 1$ dB/km.

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