Axial Temperature Distribution in W-Tailored Optical Fibers

Mohamed I. Shehata (m.ismail34@yahoo.com), **Moustafa H. Aly**(drmosaly@gmail.com) OSA Member, and **M. B. Saleh** (Basheer@aast.edu)

Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

Abstract-
In the present paper, the thermal effects in W-shaped core refractive index optical fibers are investigated. The aim is to minimize its harmful effects on the maximum axial temperature inside the fiber core by selecting suitable values for the affecting parameters. These include the index tailoring parameters, core radius, core absorption coefficient and intensity of light launched to the fiber core.

Keywords: Optical Fibers, Thermal Effects, W-Tailored Index Fibers, Maximum Axial Temperature.

I. Introduction

When a laser beam is transmitted through a medium, a portion of its power is absorbed by the medium and consequently, heats that medium and alters the temperature along the laser path. The new temperature distributions are resulted from the changes that occur in both direction of propagation and normal to it. The operation of creating a new temperature distribution is a transient process, but generally, the steady state distribution is occurred when a form of heat transfer from the medium balances the absorbed laser power. The idea of sending energy through an optical fiber is not new. In fact, fibers have been widely used to guide laser energy for industrial, medical, civil and military applications.

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Recent remarkable loss reduction in an optical fiber improves the possibility of using it in the field of communications. However, the energy transmission capacity of an optical fiber is defined by the input power that raises the temperature of the fiber to the maximum acceptable level.

Single mode (SM) optical fibers are the most suitable for the high data-rate transmission systems due to the absence of the intermodal dispersion. However, the single-clad single-mode fiber has some problems due to the difficulty in the excitation and splicing because of the small core radius [1-3].

These problems can be solved through utilizing the single-mode graded-core W-fibers that were firstly proposed by Kawakami and Nishida [4]. These W-type fibers have a larger core than that in a single-clad fiber and it are also less sensitive to the launching angle, which can increase the splicing tolerances [3].

In this paper, the thermal effects are investigated in W-shaped optical fibers carrying high power as in optical amplifiers, sensors and medical applications. Section 1 is a general introduction, Sec. 2 handles the basic model and analysis, while Sec. 3 processes the obtained results with a general discussion and Sec. 4 summarizes the major conclusions. We present a theoretical treatment, aided by Matlab program results, for the axial temperature distributions in bi-quadratic index optical fiber. The axial temperature distribution depends mainly on the laser ray trajectory.

II. Basic Model and Analysis

The solution of the ray equation [5] is the normalized radial position with respect to the core radius [$\rho = (r/a)$] as a function of the normalized propagation distance [$\eta = (z/a)$], the fiber parameters and the launching conditions.

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

where r is the radial position, a is the fiber core radius, z is the propagation distance, N_o is the direction cosine of the incident ray, while n_o is known as the axial refractive index at any incident point. In addition, n is the refractive index profile of the medium that can be expressed for W-tailored type as:

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

where α and m are tailoring parameters.

The use of $\rho_n = \rho(2m)^{1/2}$ and $\eta_n = \eta(2\alpha)^{1/2}/N_o$ into Eq. (1) gives:

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

This equation is solved numerically by a Matlab program, with initial conditions (at $\eta = 0.0$):

$$\rho_o = \rho_n\big|_{z=0} = C_0 = \frac{r_o}{a}\sqrt{2m} \quad (4)$$

and

$$\rho_o' = \frac{d\rho_n}{d\eta_n}\Big|_{z=0} = C_1 = \frac{dr}{dz}\Big|_{z=0} N_o \sqrt{\frac{m}{\alpha}} \quad (5)$$

The maximum axial temperature, T_{max}, is found by solving the energy balance differential equation [6, 7]:

$$\frac{1}{\rho}\frac{\partial}{\partial \rho}(\rho\frac{\partial T}{\partial \rho}) = -\frac{\sigma I_o a^2}{kF^2}(\frac{\rho_o}{\rho})^2 \exp(-2\sigma n_o N_o \eta - \frac{\rho^2}{F^2}) \quad (6)$$

where σ is the absorption of the medium, T is the absolute temperature at the radial position, ρ, k is the thermal conductivity of the fiber material and F is the hot spot parameter.

When a laser beam is assumed to have a Gaussian distribution, the undistorted intensity can be defined by:

$$I(\rho, z) = \frac{I_o}{F^2}\exp(-\sigma z - \frac{\rho^2}{F^2}) \quad (7)$$

where I_o is the output power intensity of laser source.

The undistorted intensity equation is subjected to the following initial conditions:

$$F\big|_{z=0} = 1.0 \text{ and } \rho\big|_{z=0} = \rho_o \quad (8)$$

Algebraic manipulation of Eqs. (6-8) yields the following differential equation:

$$\frac{dF}{dz} = \frac{\frac{zF^3}{2n_o}\frac{\partial^2 n}{\partial \rho^2} - \frac{zF\rho}{n_o}\frac{\partial n}{\partial \rho} - F\rho\frac{\partial \rho}{\partial z}}{[F^2 - \rho^2]} \quad (9)$$

The hot the spot parameter, F, can be computed numerically by solving Eq. (9). It can also be defined through the light intensity at any position (ρ, η) by:

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

The absolute temperature, T, at a radial position, ρ, can be obtained by solving the energy balance differential equation [8]:

$$\frac{1}{\rho}\frac{\partial}{\partial \rho}(\rho\frac{\partial T}{\partial \rho}) = -\frac{\sigma I_o a^2}{kF^2}(\frac{\rho_o}{\rho})^2 \exp(-2\sigma n_o N_o \eta - \frac{\rho^2}{F^2}) \quad (11)$$

where k is the thermal conductivity of the fiber material.

The heat flux across the hot path-cold region interface is proportional to the temperature difference between the surface and the surrounding medium. By definition of thermal conductivity, k, and the convection heat transfer coefficient, H, one can write:

$$\frac{k}{a}\frac{\partial T}{\partial \rho}\Big|_{\rho=\rho_w} = H(T_{max} - T_o) \quad (12)$$

where T_o is the ambient absolute temperature.

The use of Eqs. (10) and (11) into Eq. (12) yields:

$$T_{max} = T_o + 0.5A_o(0.5\rho^2 + \frac{\rho k}{Ha}) \quad (13)$$

where:

$$A_o = \frac{\sigma I_o a^2}{k}\left(\frac{\rho_o}{\rho}\right)^2 \exp(-2\sigma a N_o n_o \eta) \quad (14)$$

where I is the intensity of light launched to the fiber core.

III. Results and Discussion

The described model is used in MATLAB ver. 7 to perform calculations through this paper. The obtained ρ-η, Fig. 1, shows a periodic change.

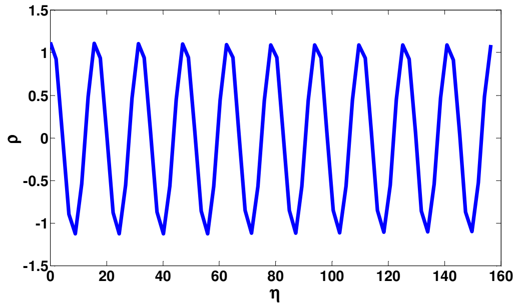

Fig. 1 The variation of ρ with η at α = 0.1 , m = 0.1 , a = 4 μm and I = 7×10^10 W/m^2.

The procedure is repeated for other values of the affecting parameters. To keep the W-shape of the core refractive index, the tailoring parameters are taken in the ranges: $0.1 \le \alpha \le 0.9$ and $0.1 \le m \le 0.9$. The core radius is taken as $2.0 \le a \le 4.o$ μm and the intensity as $1.0\times10^{10} \le I \le 9.0\times10^{10}$ W/m^2. The attempts yield the same behavior and show that the maximum value of ρ varies according to the values of the affecting parameters.

The obtained values of ρ are used to get the maximum temperature, T_{max}, Eq. (9), and the results are displayed in Figs. 2-8 for different values of the controlling parameters.

The effect of the controlling parameter α is first investigated and the results obtained in Figs. 2-6 show that α has a negligible effect on the value of the maximum axial temperature.

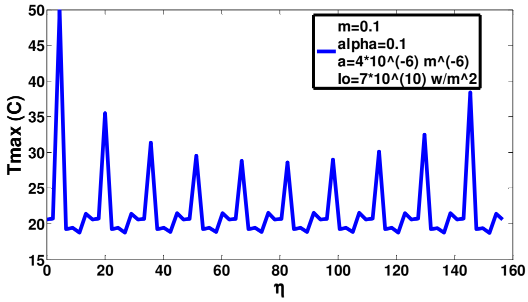

Fig. 2 The variation of T_{max} with η at α = 0.1

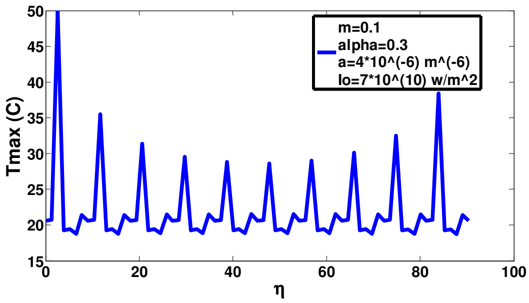

Fig. 3 The variation of T_{max} with η at α = 0.3

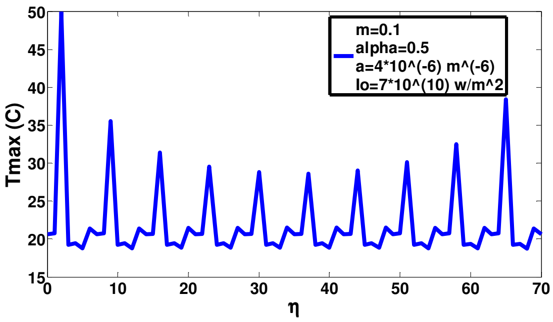

Fig. 4 The variation of T_{max} with η at α = 0.5

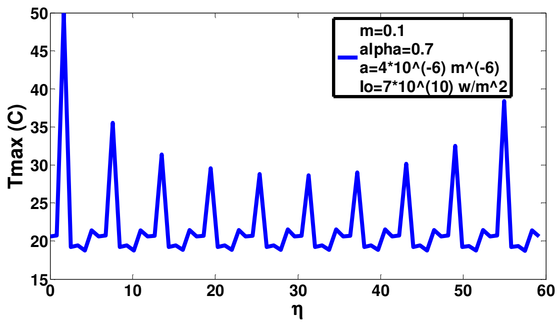

Fig. 5 The variation of T_{max} with η at α = 0.7

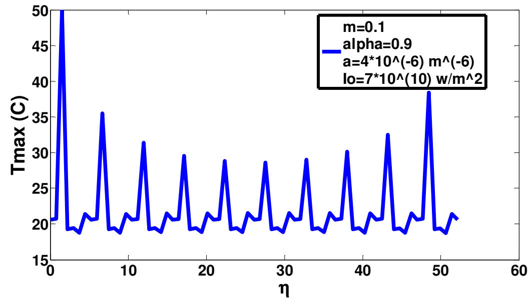

Fig. 6 The variation of T_{max} with η at α = 0.9

Through these figures, the maximum temperature is 49.89 °C and is obtained at η = 1.4907, while the minimum temperature is 28.65 °C and is obtained at η = 27.58. Both values are in the allowable range (below 60 °C) inside the silica fibers [9].

Again, the procedure of calculating the maximum axial temperature is repeated to study the effect of the second controlling parameter, m, in the range 0.1 ≤ m ≤ 0.9. Keeping the other affecting parameters constant, the obtained results are displayed in Figs. 7-11.

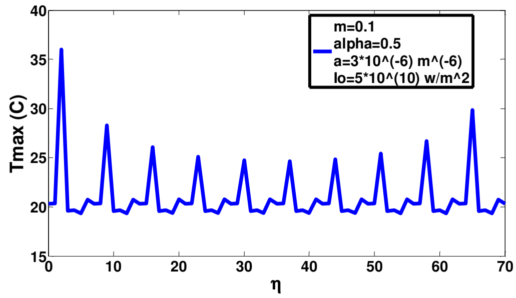

Fig. 7 The variation of T_{max} with η at m = 0.1

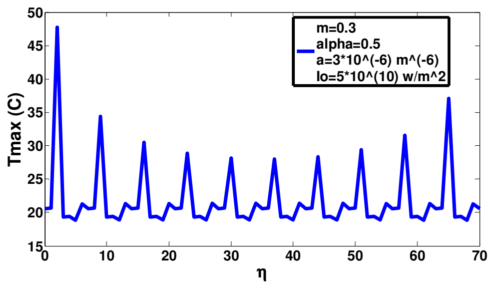

Fig. 8 The variation of T_{max} with η at m = 0.3

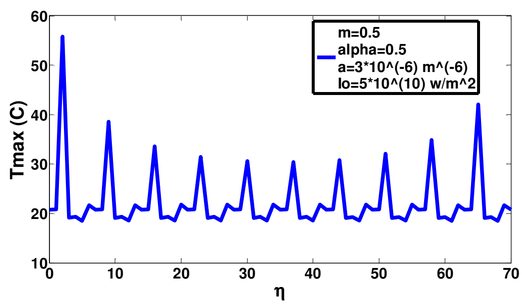

Fig. 9 The variation of T_{max} with η at m = 0.5

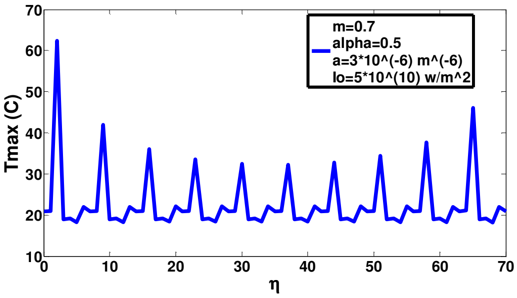

Fig. 10 The variation of T_{max} with η at m = 0.7

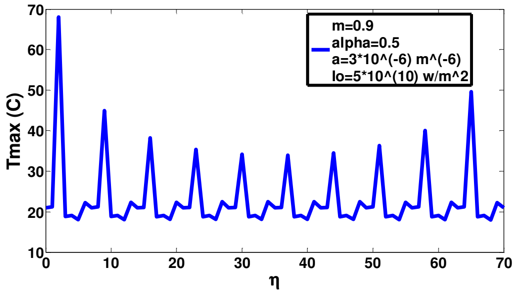

Fig. 11 The variation of T_{max} with η at m = 0.9

It is clear that the controlling parameter, m, has an appreciable effect on the maximum axial temperature. It is an effective parameter that causes temperature inside optical fiber to increase. At m = 0.1 to 0.5, the maximum axial temperature lies in the acceptable range (below 60 °C as mentioned for the silica fibers). On the other hand, at m = 0.7 to 0.9, the maximum axial temperature exceeds 60 °C and therefore, these values for the parameter m must be excluded for the correct fiber design.

Finally, we study the effect of the output power intensity of the light source, I_o, which is launched to the fiber core. Figures 12-16 depict the axial temperature distribution. As expected, the maximum axial temperature is strongly affected by the intensity. Therefore, one can consider its effect as the most important and effective one that raises temperature inside optical fiber. Greater values of the intensity cause temperature values over the accepted level and therefore are rejected.

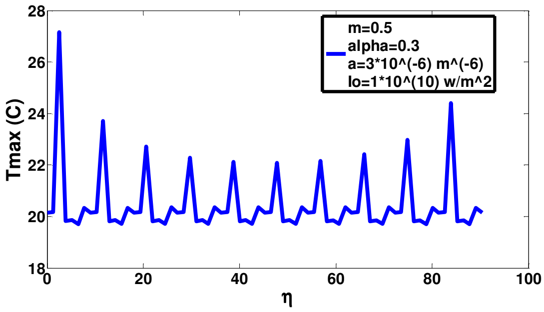

Fig. 12 The variation of T_{max} with η at $I_o = 1\times10^{10}$ W/m^2

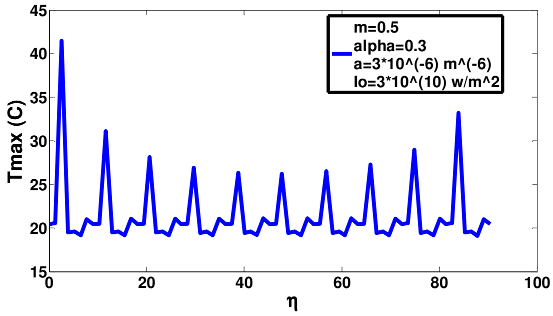

Fig. 13 The variation of T_{max} with η at $I_o = 3\times10^{10}$ W/m^2

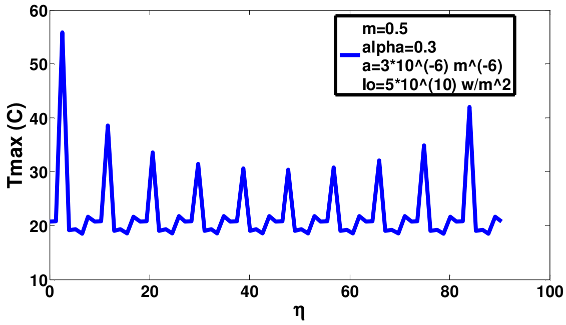

Fig. 14 The variation of T_{max} with η at $I_o = 5\times10^{10}$ W/m^2

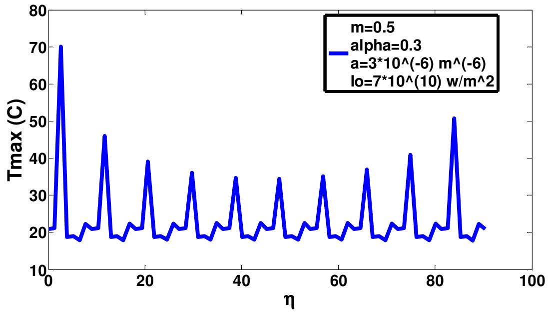

Fig. 15 The variation of T_{max} with η at $I_o = 7\times10^{10}$ W/m^2

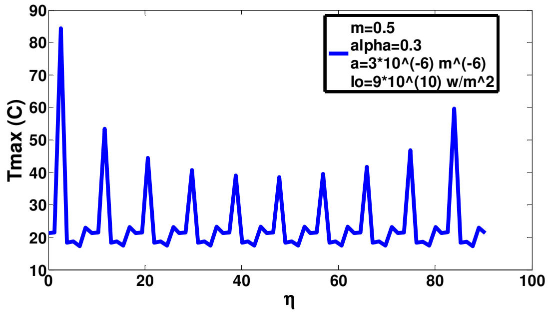

Fig. 16 The variation of T_{max} with η at $I_o = 9\times10^{10}$ W/m^2

4. Conclusion

Maximum axial temperature represents a critical factor in the thermal effect of optical fibers. A quantitative study for its value inside a W-shaped core refractive index fiber is carried out. The maximum axial temperature was calculated for different independent variables in different ranges. The affecting parameters include the core radius, the tailoring parameters of the refractive index and the intensity of light launched to the fiber core. The obtained values of the maximum axial temperature, T_{max}, are summarized in Table 1.

m	α	a(μm)	$I_o \times 10^{10}$ (W/m^2)	T_{max}(^{o}C)
0.1	0.1	4	7	49.8881
0.1	0.3	4	7	49.8881
0.1	0.5	4	7	49.8881
0.1	0.7	4	7	49.8881
0.1	0.9	4	7	49.8881
0.1	0.5	3	5	36.0115
0.3	0.5	3	5	47.7327
0.5	0.5	3	5	55.8028
0.7	0.5	3	5	62.3624
0.9	0.5	3	5	68.0345
0.5	0.3	3	1	27.1606
0.5	0.3	3	3	41.4817
0.5	0.3	3	5	55.8028
0.5	0.3	3	7	70.1235
0.5	0.3	3	9	84.4450

Table 1 Maximum axial temperature at different independent parameters.

Based on Ref. [9], the maximum axial temperature inside optical fiber is to be acceptable below 60 ^{o}C. So, the table can easily be used to get the correct design parameters of the core refractive index and core radius for the practical use of the W-tailored fiber. Again, the table shows that the light intensity has the greatest effect on the axial temperature.

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