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Papers' Titles and Authors	Pages
Dynamics of Electrons in Free Electron Laser with Square Core Waveguides Farkhondeh Allahverdi, Amir Hossein Ahmadkhan Kordbacheh, and Farideh Allahverdi	69-79
Optical and Thermal Properties of Mixed Alkali Phosphate Based Glasses Samira Vafaei and Mohammad Hossein Hekmatshoar	81-90
Propagation and Interaction of Electrostatic and Electromagnetic Waves in Two Stream Free Electron Laser in the Presence of Self-Fields Taghi Mohsenpour, Hasan Ehsani Amri, and Zahra Norouzi	91-100
An Analytical Model for Rare Earth Doped Fiber Lasers Consisting of High Reflectivity Mirrors Fateme Kazemizadeh, Rasoul Malekfar, and Fateme Shahshahani	101-110
Photonic Crystal-Based Polarization Converter for Optical Communication Applications Mahmoud Nikoufard and Mohsen Hatami	111-116
Linear and Nonlinear Dust Acoustic Waves in Quantum Dusty Electron-Positron-Ion Plasma Elham Emadi and Hossein Zahed	117-122
Analysis of Protein Concentration Based on Photonic Crystal Ring Resonator Savarimuthu Robinson and Krishnan Vijaya Shanthi	123-130

In the name of God, the Compassionate, the Merciful

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An Analytical Model for Rare Earth Doped Fiber Lasers Consisting of High Reflectivity Mirrors

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ABSTRACT— The present article is concerned with an analytical solution for some parts of rare earth doped fiber laser equations. The presented model is valid for both four and three-level fiber lasers consisting high reflectivity mirrors. A typical method to obtain initial value in the numerical solutions of fiber laser equations is shooting method, which is based on an iteration process. Whereas this standard method needs to repeat computational loops to correct an initial guess value in order to satisfy the boundary conditions, which is a time consuming task.

The model and its analytical solution, presented in this article, and the accuracy of the obtained values reveals that the method significantly reduces the time computation. The proposed method has been used for an erbium doped fiber laser and it shows that when the reflectivity of mirrors is more than 0.6 (60%), the calculated results are in agreement with the results of standard numerical methods and the error is less than 10 percent.

KEYWORDS: Analytical method, erbium doped fiber lasers, fiber lasers, numerical solution.

I. INTRODUCTION

Rare earth doped fiber lasers and amplifiers have been studied vastly over the last decades, because of their attractive properties such as optical confinement and compact geometry. They are very efficient and high-quality sources for many applications. In order to optimize the performance of fiber lasers and amplifiers, accurate theoretical models that could predict experimental results, play an

important role. A theoretical model which is applied for analyzing the rare earth doped fiber lasers is well known as standard model. This model is based on solving the rate and differential equations which explain evolution of the optical pump and signal power [1-6]. An iteration process, named shooting method, is used to correct an initial guess for the initial signal intensity values, which continues to run until the boundary conditions are satisfied. So the standard numerical method is too time consuming. Many efforts have been done to reduce the computation time. Several analytical models, based on different simplified assumptions, can be found in literatures [7-12]. The analytical model has been presented in [7-8] which is valid for strongly pumped fiber lasers. This approximation model is mostly suitable for four and quasi-three level laser systems and also for double clad fiber lasers and not for low power fiber lasers. The analytical model for determination of optical output reflectivity and fiber length in erbium doped fiber lasers (EDFLs) without the z-dependency of parameters has been reported [9]. Reference [10-11] gives an analytical model expressed in terms of easily measured parameters. Another analytical model based on using average population density of upper state of laser can be found in [12]. But there is no good comparison between this analytical models and numerical methods. In addition there are always limitations for analytical models that restrict their application.

So, in order to have a comprehensive model, it is preferred to use numerical methods despite being time consuming. Some investigations have improved the accuracy of shooting method by initial guess functions [13-14]. These works have been performed for double clad high power lasers and is not suitable for the fiber lasers and are intended in this article. To the best of our knowledge there is no good model for improving the shooting method for low power one clad fiber lasers which are very widely used in telecommunication systems.

The main goal in this paper is to describe a method for prediction of an accurate initial guess for solving the standard model for low power one clad fiber lasers. Using this method can eliminate the use of shooting method, and the numerical computation time significantly decreases compared to the standard model. The presented method is valid for both four and three-level laser systems. We have considered the low-power fiber lasers, so we can ignore scattering losses and interactions between neighboring ions. The validity of the model has been investigated for an erbium-doped single-mode fiber laser at $\lambda_s=1530$ nm pumped at $\lambda_p=980$ nm. Although the model is not necessarily limited to trivalent EDFLs, we are mainly interested in erbium for its vast application in researches and in high-speed fiber optics communications [15].

The article is organized as follows: section II is assigned to the theory and physical model, and our new method for determining the initial value is presented. In section III the validity of new introduced model has been investigated and the numerical results based on new method have been compared with the standard model. Conclusions are given in section IV.

II. THEORETICAL MODELS

Rate equations in a rare earth doped fiber laser are given by [4]:

$$\frac{dN_1}{dt} = -\frac{dN_2}{dt} = -w_a N_1 + w_e N_2 - R_{13} N_1 + \frac{1}{\tau_2} N_2 \quad (1)$$

where N_1 and N_2 are the population densities of the ground (${}^4I_{15/2}$) and the upper (${}^4I_{13/2}$)

states, respectively, subscript a and e denote the absorption and emission, τ_2 is the lifetime of upper state, w_e , w_a , and R_{13} are emission, absorption, and pump rates, respectively, and can be defined as follows:

$$R_{13} = \frac{\sigma_p I_p}{h \nu_p} \quad (2)$$

$$w_{a,e} = \frac{\sigma_{a,e} I_s}{h \nu_s} \quad (3)$$

where I_p and I_s are the pump and signal intensities, respectively. σ_a and σ_e are the absorption and emission cross-sections for signal wavelength and σ_p is the absorption cross-section for pump wavelength. h is the Planck constant and ν_p and ν_s are the frequencies of pump and signal, respectively.

The steady-state solution of Eq. (1) leads to population densities, N_1 and N_2 , [4]:

$$N_1 = \frac{w_e + \frac{1}{\tau_2}}{w_a + w_e + \frac{1}{\tau_2} + R_{13}} N_0 \quad (4)$$

$$N_2 = \frac{w_a + R_{13}}{w_a + w_e + \frac{1}{\tau_2} + R_{13}} N_0 \quad (5)$$

Since N_3 and N_4 , which are the population densities of third and fourth states respectively, are negligible, the total population density N_0 satisfies $N_0 = N_1 + N_2$. The evolutions of optical pump and optical signal intensities along the active medium can be expressed as [4]:

$$\frac{dI_p}{dz} = -(\sigma_p N_1 + \sigma'_p N_2) I_p(r, \varphi, z) \quad (6)$$

$$\frac{dI_s}{dz} = (\sigma_e N_2 - \sigma_a N_1) I_s(r, \varphi, z) \quad (7)$$

where σ'_p is the absorption cross-section for excited state absorption effect. The intensities I_p and I_s can be assumed as:

$$I_p(r, \varphi, z) = P(z) \rho_n(r, \varphi) \quad (8)$$

$$I_s(r, \varphi, z) = S(z)S_0(r, \varphi) \quad (9)$$

where $P(z)$ and $S(z)$ describe the z -evolution of respectively the pump and signal waves along the fiber length and can be normalized. $\rho_n(r, \varphi)$ and $S_0(r, \varphi)$ are transverse power distribution of pump and signal, respectively. n denotes the mode number and is equal to 0 for the fundamental mode. assuming that the signal is single mode, n can be replaced by zero for the signal. By replacing population densities from (4) and (5), propagation equations of the pump and signal powers along the fiber laser can be obtained:

$$\frac{dP^\pm(z)}{dz} = \mp \alpha_p \frac{2\pi}{\beta A} \frac{P^\pm(z)}{P^+(z) + P^-(z)} \times \int_{r=0}^a \kappa_n(r, z) [1 + S_t] r dr \quad (10)$$

$$\frac{dg(z)}{dz} = -\alpha_a \eta_s + 2\pi \alpha_a (1 + \gamma_s) \times \int_{r=0}^a S_0(r) \left\{ \frac{A \gamma_s S_t + \kappa_n(r, z) [1 + A S_t]}{1 + A (1 + \gamma_s) S_t} \right\} r dr \quad (11)$$

where a the radius of the fiber core, $g(z)$ is the gain in decibel and is equal to $10 \log(S(z))$. S_t , γ_s , β , β_e , $\kappa_n(r, z)$, and $C_n(r, z)$ are as follows:

$$S_t = \beta_e S_0(r) (S^+(z) + S^-(z)) \quad (12)$$

$$\gamma_s = \frac{\sigma_a}{\sigma_e} \quad (13)$$

$$\beta = \frac{\sigma_p \tau_2}{h \nu_p} \frac{P_p(0)}{A} \quad (14-1)$$

$$\beta_e = \frac{\sigma_e \tau_2}{h \nu_s} \frac{P_s(0)}{A} \quad (14-2)$$

$$\kappa_n(r, z) = \begin{cases} 1 - \frac{1}{1 + C_n(r, z)}, & n = 0 \\ 1 - \frac{1}{(1 + C_n(r, z))^{1/2}}, & n > 0 \end{cases} \quad (15)$$

$$C_n(r, z) = \frac{\beta A (P^+(z) + P^-(z)) r_n(r)}{1 + (1 + \gamma_s) S_t} \quad (16)$$

$P_p(0)$ and $P_s(0)$ are the pump and signal powers at $z=0$, respectively. $r_n(r)$ is the radial part of transverse power distribution of pump in Eq. (8), β and β_e are the saturation parameters and $\alpha_{p,a}$ represent the plane wave absorption coefficient of the core material at $\lambda_{p,s}$ and is equal to $\alpha_{p,a} = \sigma_{p,a} N_0$. Signs of + and - denote the forward and backward transmission directions, respectively. n is the number of modes. η_s and η_p are the fractional signal and pump energy contained in the fiber core and can be calculated by [4]:

$$\eta_s = 2\pi \int_{r=0}^a S_0(r) r dr \quad (17)$$

$$\eta_p = \int_{r=0}^a \int_{\varphi=0}^{2\pi} \rho_n(r, \varphi) r dr d\varphi = \pi e_n \int_{r=0}^a r_n(r) r dr \quad (18)$$

The coefficient e_n in (18) is equal to 2 for the fundamental mode and is equal to 1 for other modes [4]. If we apply a very narrow signal bandwidth, we can use $S^\pm(z, \lambda) \cong S^\pm(z) \delta(\lambda - \lambda_s)$, so the integrals over wavelength reduced to $S^\pm(z, \lambda_s)$.

Eqs. (10)-(11) should be solved subject to the boundary conditions:

$$\begin{cases} S^+(0) = R_2(\lambda_s) S^-(0) \\ S^-(L) = R_1(\lambda_s) S^+(L) \\ S^+(0) S^-(0) = S^+(L) S^-(L) = c \end{cases} \quad (19)$$

where R_2 and R_1 are the power reflectivity of the Bragg reflectors at $z=0$ and $z=L$, respectively. c is a constant. Similar equations are satisfied for the pump power. A way for solving these equations is the shooting method, which starts from an initial guess and treats the problem as an initial value problem. Then an iteration method is used to correct the initial guess until the boundary conditions are satisfied [5, 16]. By using the below mentioned algorithm, the initial value is determined and it is not necessary to use the shooting method or any other time consuming and complex methods. We can use the following equations instead of Eqs (10)-(11)

by ignoring the radial integrations and entering the confinement factors:

$$\frac{dP^{\pm}(z)}{dz} = \mp \alpha_p \Gamma_p P^{\pm}(z) \times \frac{1 + \left(\frac{2\sigma_e}{\sigma_e + \sigma_a} \right) \frac{P_s(0)}{S^{sat}} (S^+(z) + S^-(z))}{1 + 2 \frac{P_s(0)}{S^{sat}} (S^+(z) + S^-(z)) + \frac{P_p(0)}{P^{sat}} (P^+(z) + P^-(z))} \quad (20)$$

$$\frac{dS^{\pm}(z)}{dz} = \mp \Gamma_s S^{\pm}(z) \times \frac{\alpha_e \frac{P_p(0)}{P^{sat}} (P^+(z) + P^-(z)) - \alpha_a}{1 + 2 \frac{P_s(0)}{S^{sat}} (S^+(z) + S^-(z)) + \frac{P_p(0)}{P^{sat}} (P^+(z) + P^-(z))} \quad (21)$$

The overlap integral or confinement factors, Γ_p and Γ_s , account for the transverse overlap of optical wave with the dopant ions, and A_{eff} represents the effective area. P^{sat} and S^{sat} are the pump and signal saturation powers which are defined by:

$$P^{sat} = \frac{h\nu_p A_{eff}}{\sigma_p \tau_2 \Gamma_p} \quad (22)$$

$$S^{sat} = \frac{h\nu_s}{\left(\frac{\sigma_e + \sigma_a}{2} \right) \tau_2} \frac{A_{eff}}{\Gamma_s} \quad (23)$$

The detailed derivations of these parameters are given in [10]. If the reflectivity of the mirrors be more than 0.6, we can easily replace $(S^+(z) + S^-(z))$ by $2P_s(0)$ [4]. This approximation is useful for both of the numerical and analytical solutions. We assume that the mirrors are transparent for the pump beam wavelength and also the backward pump power is equal to zero. A nonlinear equation will be obtained by integrating the Eq. (20) along the fiber length:

$$\left(4 \frac{P_s(0)}{S^{sat}} + 1 \right) \ln P(z) + \frac{P_p(0)}{P^{sat}} (P(z) - 1) = -\alpha_p \Gamma_p \left(1 + \frac{\sigma_e}{\sigma_e + \sigma_a} \frac{4P_s(0)}{S^{sat}} \right) z \quad (24)$$

Similar equation can be obtained for the signal power. By rewrite (21) versus $dP(z)/dz$ we obtain:

$$\frac{dS^{\pm}(z)}{dz} = \mp \Gamma_s \frac{dP(z)}{dz} S^{\pm}(z) \times \frac{\alpha_e \frac{P_p(0)}{P^{sat}} P(z) - \alpha_a}{-\alpha_p \Gamma_p \left(1 + \left(\frac{4\sigma_e}{\sigma_e + \sigma_a} \right) \frac{P_s(0)}{S^{sat}} \right) P(z)} \quad (25)$$

By integrating the above differential equation we can deduce a nonlinear equation for the signal power:

$$\ln S^+(z) = -\frac{\Gamma_s}{\alpha_p \Gamma_p} \left[\frac{1}{1 + \frac{\sigma_e}{\sigma_e + \sigma_a} \frac{4P_s(0)}{S^{sat}}} \right] \times \left[\alpha_e \frac{P_p(0)}{P^{sat}} (P(z) - 1) - \alpha_a \ln P(z) \right] \quad (26)$$

Applying the boundary conditions (19), the following equation can be obtained:

$$S^+(L) = \frac{1}{\sqrt{R_1 R_2}} S^+(0) \quad (27)$$

By using (24), (26) and (27), the two following equations will be attained:

$$\begin{cases} P_s(0) = -\frac{\ln P(L) + \alpha_p \Gamma_p L + \frac{P_p(0)}{P^{sat}} (P(L) - 1)}{\frac{4}{S^{sat}} \ln P(L) + \frac{4}{S^{sat}} \frac{\sigma_e}{\sigma_e + \sigma_a} \alpha_p \Gamma_p L} \\ P_s(0) = \frac{S^{sat}}{2 \ln \left(\frac{1}{\sqrt{R_1 R_2}} \right)} \left[-\frac{\alpha_e \Gamma_s}{\alpha_p \Gamma_p} \frac{P_p(0)}{P^{sat}} (P(L) - 1) + \frac{\alpha_e \Gamma_s}{\alpha_p \Gamma_p} \ln P(L) - \ln \left(\frac{1}{\sqrt{R_1 R_2}} \right) \right] \end{cases} \quad (28)$$

$P(L)$ and $P_s(0)$ can be achieved by solving these equations with any standard technique. The value of $P_s(0)$, which is obtained from Eq. (28), can be considered as an initial guess value for solving the Eqs. (24) and (26).

III. RESULTS AND DISCUSSION

In order to show the accuracy of the relation $S^+(z) + S^-(z) = 2P_s(0)$, the dependence of the output power on the reflectivity of output

mirror in an EDFL has been shown in Figs. 1, 2, and 3. Fig. 1 shows the results for a laser with length of 8m and for different pump powers.

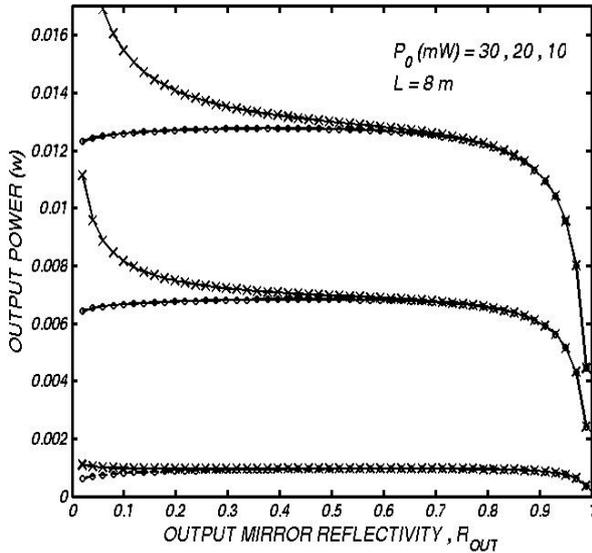


Fig. 1. Output power versus the reflectivity of output mirror, for an EDFL with three different input pump powers. The lines marked with cross represent the approximate solution and the lines marked with dots show the exact model.

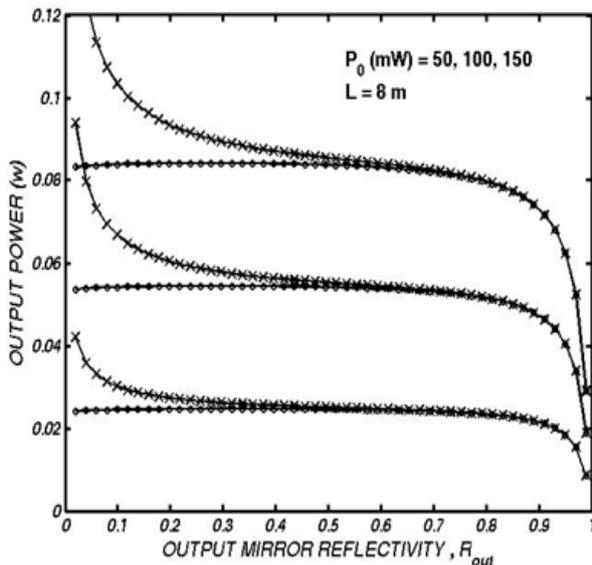


Fig. 2. Output power versus output mirror reflectivity for an EDFL with three different input pump powers. The cross and dotted marked lines represent the approximate solution and the exact model results, respectively.

This figure shows that at high reflectivity two curves are coincident and the output powers are almost equal when $R_{output} > 0.6$. It is shown

in Fig. 2 that the similar results can be obtained for higher pump powers.

Fig. (3) shows the output power versus output mirror reflectivity. The pump power is 50 mW and $L=8, 20,$ and 1 meters.

The greatest power is related to the $L=8$ m, as this is the optimum length. The cross and dotted marked lines represent the approximate solution and the exact model results, respectively.

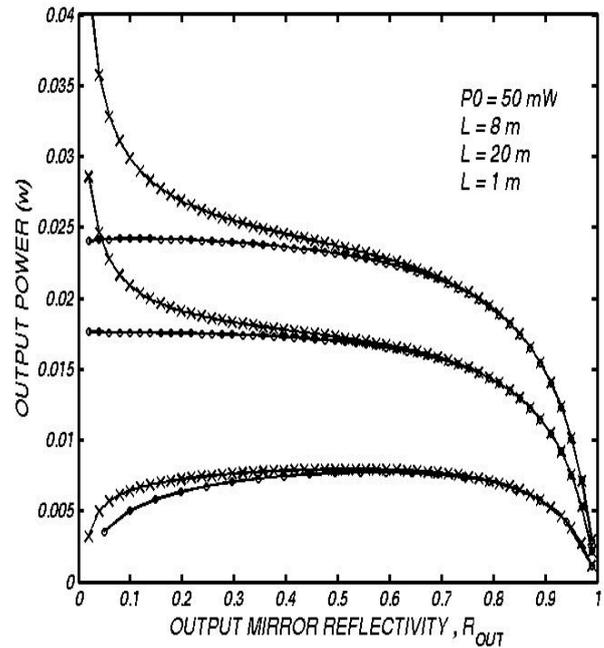


Fig. 3. Output power versus output mirror reflectivity for three different fiber lengths. Cross marked lines represent the approximate solution and dot marked lines are for exact solution.

The numerical calculations of standard model and our proposed new method are described in flowcharts 4.a and 4.b, respectively. It is clear that the computation time in new method has been significantly reduced.

The EDFL's equations have been solved by both standard and our new analytical method in order to show the validity of the new proposed model. The variation of the output power of an EDFL versus launched pump power for different fiber lengths, $L=1, 10,$ and 20m have been plotted in Fig. 5.

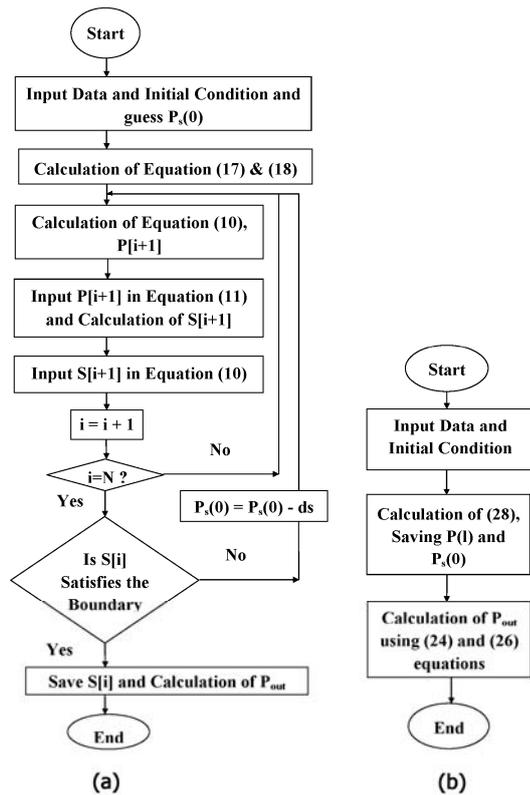


Fig. 4. The flowcharts of numerical (a) and new model (b) solutions.

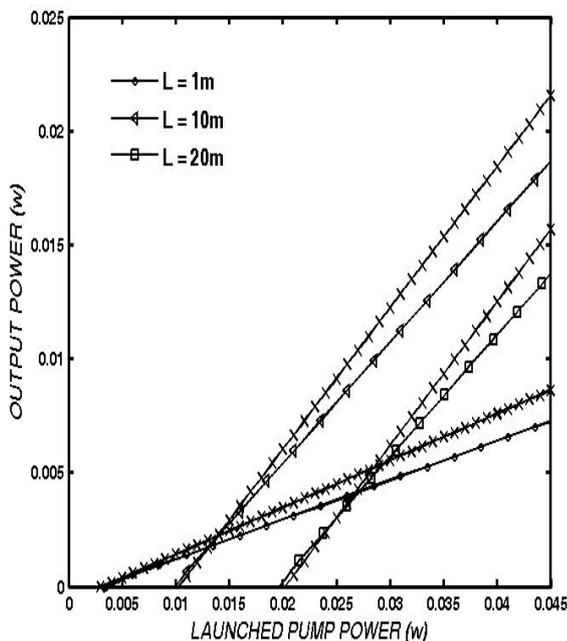


Fig. 5. Variation of output power versus the pump power for three different fiber lengths. Rectangular, cubic and dot marked lines represent the standard solution and cross marked lines are related to our model.

The output mirror reflectivity is 0.9, which satisfies the high reflectivity condition. The cross marked lines are related to our new

method and other marked lines represent the output power for different length that have been solved by standard model. Fig. 5 shows that the standard model and our model can be achieved to the same results for threshold pump power. But the slope of lines is higher at our model and the difference between two models increases as the pump power increases.

Figure 6 shows the variation of output power as a function of fiber length for three different values of pump power, $P_p(0)=10, 30,$ and 50 mW.

It is notable that the optimum length of laser has the same value for two models. Again it can be revealed that by increasing the launched pump power, the difference between accurate and analytical models tends to higher values.

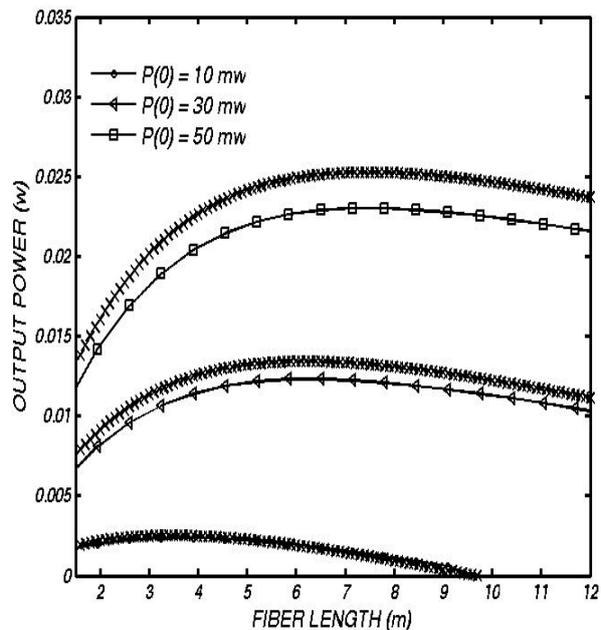


Fig. 6. Output power versus fiber length for three different input pump powers. Rectangular, cubic and circular marked lines are related to standard model and cross marked lines are for our new method.

Figure 6 shows that when the pump power is small ($P_p(0)=10$ mw), the difference between two methods is negligible. The difference between output powers resulted from standard and our analytical models, for higher pump powers ($P_p(0)=30$ and 50 mW), has been shown in Fig. 7. According to this figure, even

for high pump powers the relative difference of output power is less than 10 percent. So we can claim that there is a good agreement between our model and the numerical standard model.

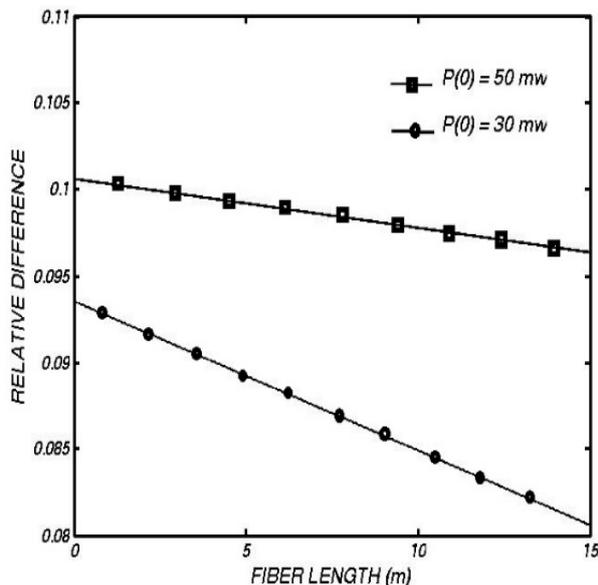


Fig. 7. The difference between output powers resulted from standard and analytical models versus fiber length for two different input pump powers.

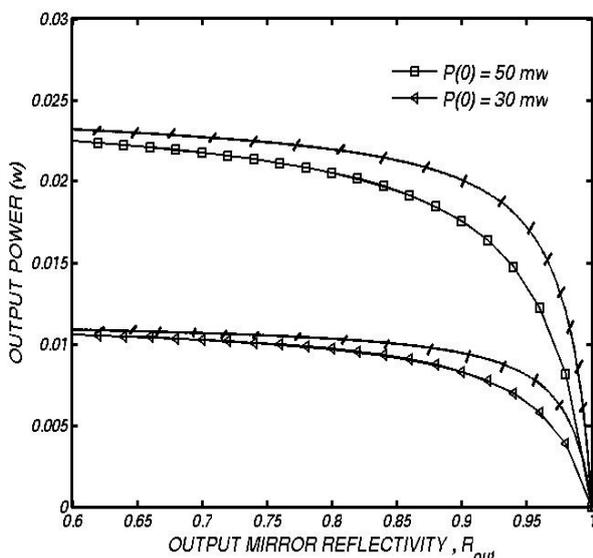


Fig. 8. Output power versus output mirror reflectivity for two different input pump powers. Input mirror reflectivity is set to 0.98. Triangular and cubic marked lines represent standard solution and cross marked lines are for our proposed new method.

Figure 8 shows the relation between the output power and the output mirror reflectivity as a function of input pump power. The input

mirror reflectivity is equal to 0.98 in the interval reflectivity limits of 0.6 to 1, which satisfies the high reflectivity condition.

Fig. 8 shows that by increasing the input pump power, the optimum output mirror reflectivity tends to lower coefficients. In addition, the difference between the results decreases for smaller mirror reflectivity. In Figs. 5 and 6, the output reflectivity was set to 0.9 and was the same for all input pump powers. Fig. 8 shows that the mentioned 10 percent error can decrease if we choose the optimum output mirror reflectivity which is about 0.6 for this example.

IV. CONCLUSION

To the best of our knowledge, the analytical works carried out on fiber lasers are related to high power double clad lasers in which their equations; due to the approximations made to solve the equations; differ slightly with single clad lasers equations. We believe there is no report for analytical method for low power fiber lasers. Accordingly, we have presented a new method for estimating the initial values of standard numerical method which can be applied for analyzing the fiber lasers. It is shown that the new proposed method is valid for lasers with the end mirror reflectance coefficient larger than 0.6. The new method significantly decreases the computation time. It is shown that the relative difference between the results of standard and our analytical models is less than 10 percent and the results of our model can be more accurate if the parameters of lasers such as the output mirror reflectivity and the fiber length can be optimized. Although the presented results have been discussed for an EDFL, but the introduced method can also be applied for four-level fiber lasers.

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