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Adaptive shooting method for 4-point side-pumping high power Yb^{3+}-doped double-clad fiber lasers

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ABSTRACT

An adaptive shooting method for solving 4-point side-pumping high power Yb^{3+}-doped double-clad fiber lasers (YDCFLs) is developed. The adaptive shooting method combines the simple identification process and shooting method procedure. Simulation results show that the adaptive shooting method can identify automatically and easily eight different cases in the 4-point side-pumping YDCFLs with different pump schemes. The initial estimate values of pump powers as independent variables are given approximate expressions and the signal powers are set random functions to speed the adaptive shooting method. The adaptive shooting method can succeed rapidly to get the exact results after average less than eight iteration steps updating initial guess values.

1. Introduction

In recent years, high power Yb^{3+}-doped double-clad fiber lasers (YDCFLs) and related pump technologies have been attracting increasing attention. A highly efficient cladding-pumped Yb^{3+}-doped fiber laser generating >2.1 kW of continuous-wave output power at 1.1 μm has been demonstrated [1]. Compared with end-pumping scheme, multipoint pump scheme can overcome the limitation of pump source and thermal effect in YDCFLs [2,3]. Many pump technologies such as embedded-mirror side pumping [4], monolithic integrated all-glass combiner [5,6] and side-pump coupler with refractive index valley configuration [7] have been developed for multipoint single or bidirectional side pumping Yb^{3+}-doped fiber lasers.

Many shooting methods have been applied for the solution of YDCFLs [8–10]. Shooting methods are sensitive to initial guess values and unsuitable initial guess values may lead shooting methods to fail. That is, when the guess is too poor for shooting methods, the backward pump power or backward signal power is lower than 0 which is unable to meet the practical physical problems [8]. A fast and stable shooting algorithm, using the Newton–Raphson method to solve the two-point boundary value problem of linear-cavity YDCFLs, has been demonstrated [9]. However, the initial estimate, given only several simple data, may bring the shooting method to fail or unable to converge to the exact solutions. A combined algorithm [10] with shooting method and relaxation method has been studied for solving the model of YDCFLs. Since both shooting method and relaxation method need suitable predicted variable initial value, the combined algorithm is very doubtful to succeed to converge. Shooting method with simple control strategy successfully deal with poor initial guess values of the backward signal and pump powers by random functions in end pumping YDCFLs [8]. However, it is very difficult and slow for solving n-point pumping YDCFLs only using random functions adjusting initial guess values of $2(n-1)$ independent variables. In addition, the backward pump powers cannot be taken as independent variables when the backward pump powers are nearly to zero, which lead to fail or convergent to error results in multipoint pump YDCFLs.

An adaptive shooting method is developed for solving the above problems in multipoint pump YDCFLs. For simplicity, the 4-point side-pumping YDCFLs is only discussed in this paper.

2. 4-Point side-pumping Yb^{3+}-doped double-clad fiber lasers model

A typical 4-point side-pumping high power linear cavity Yb^{3+}-doped fiber laser is described schematically in Fig. 1. For the 4-point side-pumping YDCFLs, pump positions $z = L_1$ and $z = L_2$ divide Yb^{3+}-doped fiber into 3 intervals $[0, L_1]$, $[L_1, L_2]$, $[L_2, L]$. Signal stimulated emission and absorption, stimulated emission at the pump wavelength and scattering losses both for the signal and the pump are considered, but spontaneous emission and excited

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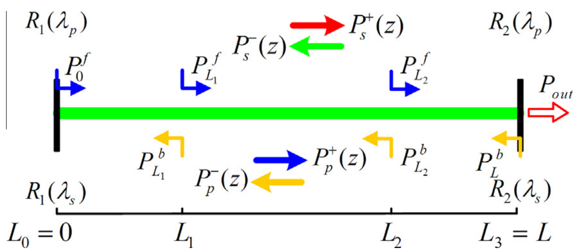

Fig. 1. Schematic illustration of 4-point side-pumping high power Yb^{3+}-doped double-cladding fiber lasers (YDCFLs).

state absorption (ESA) are negligible for strong pumping conditions in the 4-point side-pumping YDCFLs [11].

The steady-state rate equations in the 4-point side-pumping YDCFLs are described by the following set of nonlinear coupled ordinary differential Eqs. (1)–(3) [12].

$$\frac{N_2(z)}{N}=\frac{\frac{\Gamma_p\sigma_{ap}\left(P_p^+(z)+P_p^-(z)\right)\lambda_p}{hcA}+\frac{\Gamma_s\sigma_{as}\left(P_s^+(z)+P_s^-(z)\right)\lambda_s}{hcA}}{\frac{\Gamma_p(\sigma_{ap}+\sigma_{ep})\left(P_p^+(z)+P_p^-(z)\right)\lambda_p}{hcA}+\frac{1}{\tau}+\frac{\Gamma_s(\sigma_{as}+\sigma_{es})\left(P_s^+(z)+P_s^-(z)\right)\lambda_s}{hcA}} \quad (1)$$

$$\pm\frac{dP_p^{\pm}(z)}{dz}=g(P_p^{\pm}(z))=-\Gamma_p\{\sigma_{ap}N-(\sigma_{ap}+\sigma_{ep})N_2(z)\}P_p^{\pm}(z)-\alpha_pP_p^{\pm}(z) \quad (2)$$

$$\pm\frac{dP_s^{\pm}(z)}{dz}=f(P_s^{\pm}(z))=[\Gamma_s\{[\sigma_{es}+\sigma_{as}]N_2(z)-\sigma_{as}N\}-\alpha_s]P_s^{\pm}(z) \quad (3)$$

where N is the rare earth ion dopant concentration. $N_2(z)$ is the upper lasing level population density. $P_p^{\pm}(z)$ and $P_s^{\pm}(z)$ are the pump power and laser signal power along the fiber, respectively. The plus and minus superscripts represent propagation along positive or negative z-direction, respectively. Γ_p and Γ_s represent respectively the pump and laser signal filling factor in the core. σ_{ap} and σ_{ep} are the pump absorption and emission cross-section, respectively. σ_{as} and σ_{es} are the laser signal absorption and the emission cross-section, respectively. λ_p and λ_s are the pump and laser signal wavelengths, respectively. The scattering losses for the pump and laser signal powers are given by α_p and α_s, respectively. A, h, c and τ is the effective core area, Planck's constant, light velocity and spontaneous lifetime, respectively.

The boundary conditions [13,14] at side pump positions $z=0, z=L, z=L_i$ $(i=1,2)$ are

$$P_s^+(0)=R_1(\lambda_s)P_s^-(0) \quad (4\text{-a})$$

$$P_s^-(L)=R_2(\lambda_s)P_s^+(L) \quad (4\text{-b})$$

$$P_p^+(0)=R_1(\lambda_p)P_p^-(0)+\eta_{p0}P_0^f \quad (4\text{-c})$$

$$P_p^-(L)=R_2(\lambda_p)P_p^+(L)+\eta_{pL}P_L^b \quad (4\text{-d})$$

$$P_{si+1}^+(L_i)=(1-l_{si})P_{si}^+(L_i)\ (i=1,2) \quad (4\text{-e})$$

$$P_{si}^-(L_i)=(1-l_{si})P_{si+1}^-(L_i)\ (i=1,2) \quad (4\text{-f})$$

$$P_{pi+1}^+(L_i)=(1-l_{pi})P_{pi}^+(L_i)+\eta_{pi}P_{L_i}^f\ (i=1,2) \quad (4\text{-g})$$

$$P_{pi}^-(L_i)=(1-l_{pi})P_{pi+1}^-(L_i)+\eta_{pi}P_{L_i}^b\ (i=1,2) \quad (4\text{-h})$$

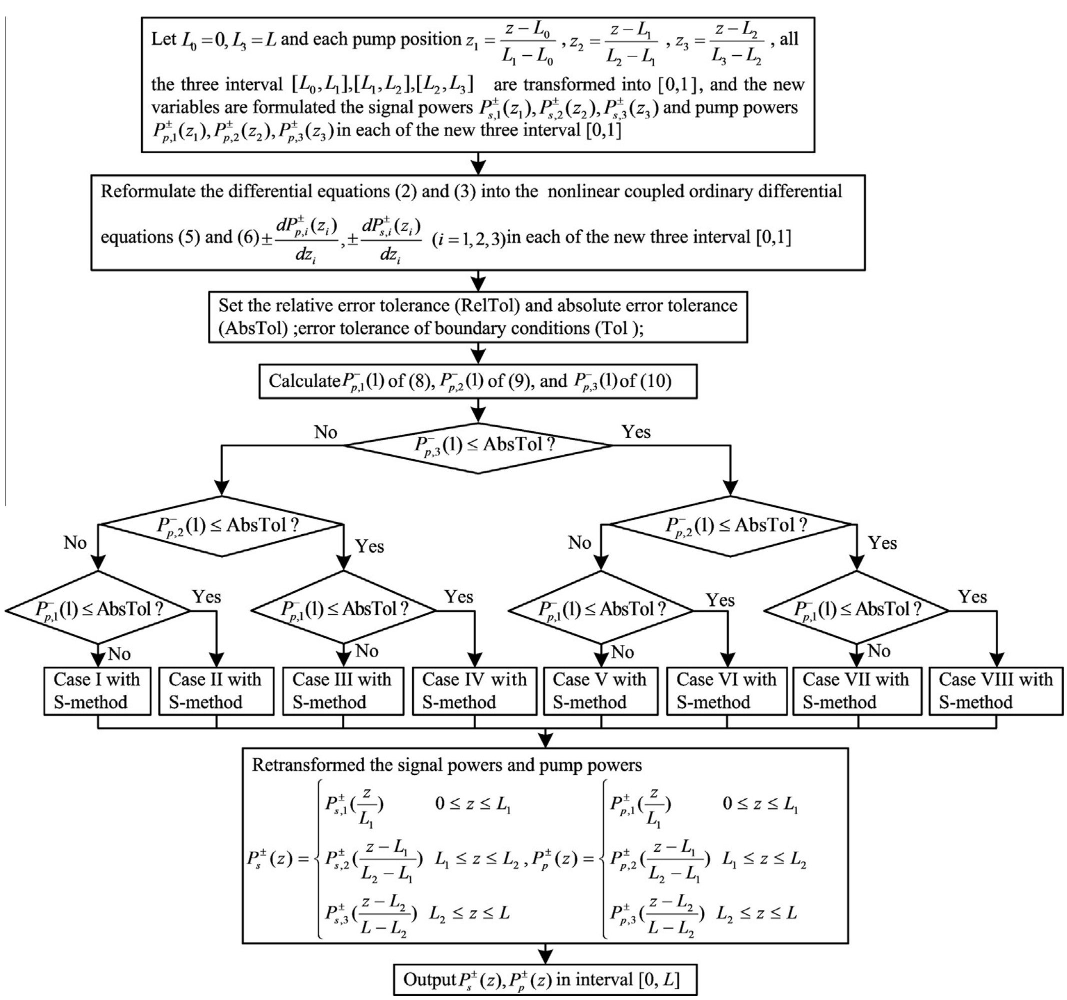

Fig. 2. The flow chart of simple identification process in the adaptive shooting method for 4-point side-pumping YDCFLs.