Novel method to optimize the distributed pump powers in a kilowatt ytterbium-doped double-clad fiber laser*

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The rate equations with multipoint boundary conditions are solved by numerical method accurately. A novel method based on genetic algorithm is proposed to optimize distributed pump powers in kilowatt YDDC fiber laser in this paper. The calculated results show that lower operation temperature and better uniformity can be achieved through an optimized pump arrangement.

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High-power ytterbium-doped fiber laser has attracted much attention recently in commercial and military applications due to its high efficiency, compactness and high beam quality. In kilowatt power domain, the heat dissipation will play an important role and affect laser performance[1,2]. The distributed pumping scheme, as the best solution, is proposed in references[3-5]. However, the method to optimize distributed pump powers wasn't discussed.

In this paper, a novel method based on genetic algorithm is proposed to optimize distributed pump powers, and the rate equations with multipoint boundary conditions are solved with numerical method accurately.

For high-power Yb-doped fiber lasers with Bragg grating reflectors strongly pumped by LDs, the pump light and output laser are of narrow spectra, which can be considered as a single wavelength. The Yb-ion is a system of three-level or quasi-three-level without pump and laser excited state absorption (ESA). We assume that under the strong pumping conditions, the spontaneous emission can be neglected, and the scattering losses for both the laser and the pump can be considered in the following. The schematic illustration and parameters are shown in Fig. 1. For cw lasers the time-independent steady-state rate equations can be expressed as[6,7]

$$\frac{N_2(z)}{N}=\frac{\dfrac{[P_p^+(z)+P_p^-(z)]\sigma_{aP}\Gamma_p}{hv_pA}+\dfrac{[P_S^+(z)+P_S^-(z)]\sigma_{as}\Gamma_S}{hv_SA}}{\dfrac{[P_p^+(z)+P_p^-(z)](\sigma_{aP}+\sigma_{eP})\Gamma_p}{hv_pA}+\dfrac{1}{\tau}+\dfrac{[P_S^+(z)+P_S^-(z)](\sigma_{as}+\sigma_{es})\Gamma_S}{hv_SA}} \quad (1)$$

$$\pm\frac{dP_p^\pm(z)}{dz}=-\Gamma_p[\sigma_{aP}N-(\sigma_{aP}+\sigma_{eP})N_2(z)]P_p^\pm(z)-\alpha_pP_p^\pm(z) \quad (2)$$

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

where N is the Yb^{3+} dopant concentration, $N_2(Z)$ is upper-level populations, $P_p^\pm(z)$ is the pump power, and $P_s^\pm(z)$ is the signal power (sign "$\pm$" corresponds to forward and backward propagations, respectively), Character A is the doped area of YDDC fiber, τ is spontaneous lifetime. Γ_p (Γ_S) is the overlapping factor between the pump (signal) and the fiber doped area, σ_{eP} (σ_{es}) and σ_{aP} (σ_{as}) are the emission and the absorption cross section of the pump (signal) light respectively, v_p is the pump frequency, v_s is the laser frequency, h is Planck's constant, α_p and α_s represent respectively scattering loss coefficients of the pump light and the laser which are independent of z.

The length from input side is L_1, L_2, L_3, respectively, as shown in Fig. 1. The pump light is separately launched into the above fiber segments through the side-coupling techniques. For the ith segment with a length of L_i, P_{PF}, i *and* P_{PB}, i stand for forward and backward pump powers, respectively. Multipoint boundary conditions associated with Eqs. (1)-(3) are considered for this case. In particular, the boundary conditions for the ith segment at $z=L_{i,1}$ and $L_{i,2}$ are given respectively by

$$P_p^+(L_{i,1})=\eta_2P_{PF,i}+\eta_3P_P^+(L_{i-1,2});P_S^+(L_{i,1})=\eta_1P_S^+(L_{i-1,2})(i=2,3) \quad (4)$$

$$P_p^-(L_{i,2})=\eta_2P_{PB,i}+\eta_3P_P^-(L_{i+1,1});P_S^-(L_{i,2})=\eta_1P_S^-(L_{i+1,1})(i=1,2) \quad (5)$$

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$$P_s^+(L_{1,1}) = R_1 P_S^-(L_{1,1});P_s^-(L_{3,2}) = R_2 P_S^+(L_{3,2}) \quad (6)$$

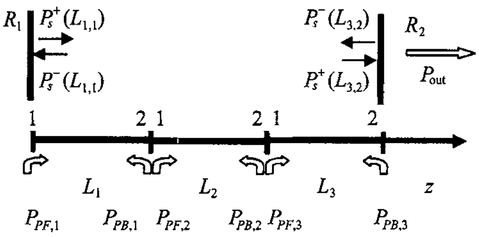

Fig. 1 Schematic of the distributed-pumping DC fiber laser

where $P_p^{\pm}(L_{i,1or2})$ and $P_s^{\pm}(L_{i,1or2})$ are the pump, signal powers, respectively, in the ith segment, η_1 and η_3 are respectively the singal and the pump transmission coefficients between the two neighboring segments, while and η_2 is the side-pump coupling efficient.

The heat dissipation as well as the transverse and longitudinal temperature distributions in the YDDC fiber under conventional air-cooling are governed by the following thermal conductive equations in symmetric cylindrical coordinates (r,z)[2]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1(r)}{\partial r}\right) = -\frac{Q(r,z)}{k}, 0 \le r \le r_1 \quad (7)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2(r)}{\partial r}\right) = 0, r_1 \le r \le r_3 \quad (8)$$

The YDDC fiber has a core diameter of 30 um ($2r_1$), an inner cladding diameter of 250 um ($2r_2$), and an outer cladding diameter of 400 um ($2r_3$). If k denotes the thermal conductivity and $Q(r,z)$ the heat density, T_1 and T_2 are the temperature in the core region and the cladding region, respectively, the boundary conditions for the Eqs. (7) and (8) can be given by

$$\left.\frac{\partial T_1(r)}{\partial r}\right|_{r=0} = 0; T_1\big|_{r=r_1} = T_2\big|_{r=r_1}; \left.\frac{\partial T_1(r)}{\partial r}\right|_{r=r_1} = \left.\frac{\partial T_2(r)}{\partial r}\right|_{r=r_1}; \left.\frac{\partial T_2(r)}{\partial r}\right|_{r=r_3} = \frac{H}{k}[T_h - T_2(r=r_3)] \quad (9)$$

where H is the convective coefficient, and T_h is the heat sink temperature. The results of Eqs. (7) and (8) can be expressed as[9]

$$T_1(r) = T_h + \frac{\alpha_a\eta_h[P_p^+(z)+P_p^-(z)]+\alpha_s[P_S^+(z)+P_S^-(z)]}{16\pi k} \times \sum_{m=1}^{\infty}\frac{(-1)^m 2^m}{m!}\left[\frac{(r/r_1)^{2m}-1}{m} + 2\ln\left(\frac{r_1}{r_3}\right) - \frac{2k}{Hr_3}\right] \quad (10)$$

$$T_2(r) = T_h + \frac{\alpha_a\eta_h[P_p^+(z)+P_p^-(z)]+\alpha_s[P_S^+(z)+P_S^-(z)]}{8\pi k} \times \sum_{m=1}^{\infty}\frac{(-1)^m 2^m}{m!}\left[\ln\left(\frac{r}{r_3}\right) - \frac{k}{Hr_3}\right] \quad (11)$$

where α_a is the absorption coefficient of pump laser, and η_h is the fraction of power turned into heat due to quantum defect.

For the multipoint boundary conditions, it is difficult to solve the rate equations with the shooting method. In this paper, the rate equations are solved with numerical method based on genetic algorithm, which has better convergence properties to get accurate numerical solution efficiently. The optimized parameters are given by: $P_S^-(L_{1,1}); P_p^-(L_{i,1}); i=1,2,3$, and the selection function can be expressed by:

$$-\left|P_S^+(L_{3,2})\,\square\,R_2 - P_S^-(L_{3,2})\right| - \sum_{i=1}^{2}\left|P_P^-(L_{i,2}) - P_{PB,i} - P_P^-(L_{i+1,1})\right|.$$

In this model, the forward and the backward pump powers in the same location are equal, that is $P_{PB,i} = P_{PF,i+1}$, $i=1,2$. For example, we take $\lambda_P = 920$ nm, $\lambda_S = 1\,090$ nm, $r_p = 0.014$, $R_1 = 0.995$, $R_2 = 0.35$, $\eta_1 = \eta_3 = 1$, $\eta_2 = 0.9$, $P_{PF,i} = P_{PB,i} = 100$ W, $L_i = 10$ m, $i=1,2,3$, and get other parameters from[7]. The result are given by Tab. 1,

Tab. 1 The calculated results at the ends of each segment

P_S^- $(L_{1,1})$	P_p^- $(L_{1,1})$	P_p^- $(L_{1,2})$	P_p^- $(L_{2,1})$	P_p^- $(L_{2,2})$	P_p^- $(L_{3,1})$	P_p^- $(L_{3,2})$	P_S^+ $(L_{3,2})$	P_S^- $(L_{3,2})$
77.884	3.4602	93.388	3.388	93.227	3.227	90	418.35	14.427

where the multipoint boundary conditions are well matched.

References[3-5] showed that lower operating temperature and more uniform heat dissipation in fibers can be obtained by optimizing the arrangement of pump powers and pump absorption coefficients. In this section, a novel method using GA is proposed to optimize the arrangement of pump powers. First, the numbers of segments, the each segment length, and the forward pump power $P_{PF,1}$ in the first segment are assumed. For this scheme, the following criteria are considered: 1) $P_{PF,1}$ is more than average pump power (the ratio of total pump power to the sum numbers of pumping points), which may be adjusted lower if the temperature at the input location is higher. 2) The first and last segment length must be long enough, and the rest segments are equal in length. 3) To further decrease the fiber temperature and to flatten its distribution, more uniform pump power distribution is necessary . Second, to improve the efficiency of calculation, the analytical expressions of forward and backward pump powers are adopted[6,7,8]. The signal power equations can be solved by the shooting method in ten seconds . The optimized parameters are the distributed pump powers in the two ends of each segment except the first forward pump power. The selection function is the stand deviation of the max temperatures, which are composed of maximum temperature in each segment. It can be expressed as $(1/(n-1))\sum_{j=1}^{n}(T_i - T_{ave})^2)^{1/2}$, where n is the total numbers of segments, T_i is the maximum temperature in each segment, and T_{ave} is the average temperature of T_i. Finally, according to the optimized pump powers, the signal and pump powers distributions along z should be calculated accurately with numerical method, and then the temperature distributions are available in "℃".

With the maximum temperature of 140 ℃, the optimal solution with seven segments is given below. The length of both the first and the last segments are 10 m, the others are identically 6 m, and the total fiber length is 50 m. The pump powers, totaling 1 000 W, is 100, 90, 74, 70, 65, 61, 59, 62 W for segment 1, 2, 3, 4, 5, 6 and 7, respectively. The temperature and power distributions in the laser cavity are depicted in Fig. 2. We can see that the maximum and the minimum temperatures at the fiber axis are 140 and 80 ℃, respectively, and the output power is 633 W.

For a fiber with the total length of 55 m divided into eight segments, the length from the input side is 10, 6, 6, 6, 6, 6, 6, 9, respectively, in which a pump power of 1 KW will be distributed into 95, 81, 68, 63, 60, 54, 50, 50 and 53 W, respectively. The temperature and power distributions in the fiber are depicted in Fig. 3, where the maximum temperature at the fiber axis is 130.5 ℃, and

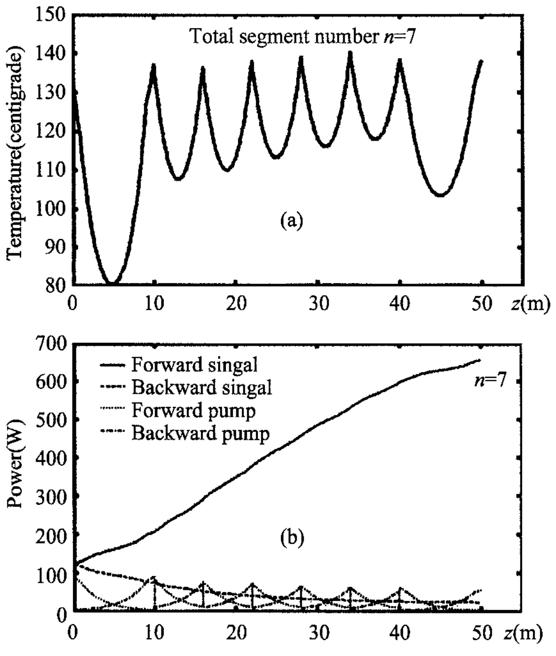

Fig. 2 Temperature and power distributions in 50 m YDDC fiber under distributed pump and with $n=7$

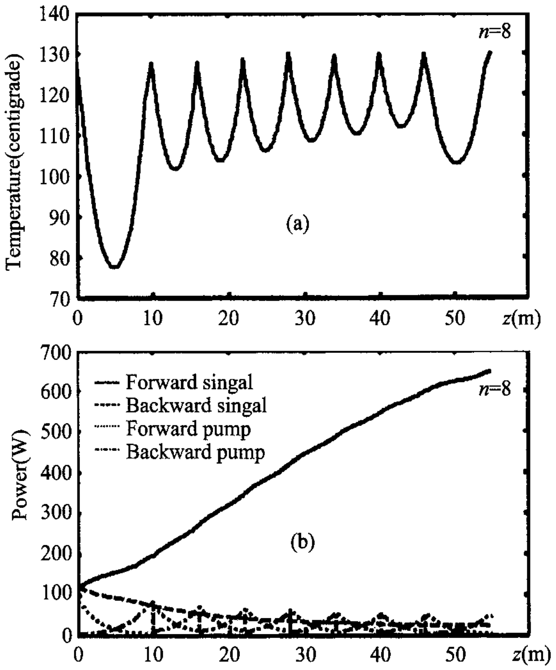

Fig. 3 Temperature and power distributions in 55 m YDDC fiber under distributed pump and with $n=8$

the output signal power is 623.88 W. Compared with the previous result in Fig. 2, it offers a lower maximum temperature and better uniformity.

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