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Thermal cooling analysis and validation of the ytterbium doped double clad fiber laser by a general analytic method

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ABSTRACT

Long optical fiber is usually coiled on the surface of the substrate. Spreading thermal resistance is an important factor affecting thermal properties of optical fiber in this encapsulation way. This paper adopts a concise general analytic method to calculate spreading thermal resistance of the eccentric heat source formed in the rectangular channel. The on-site testing of active doped double clad fiber(DDCF)laser is also carried out. It is observed that the output light efficiency is high after the fiber loses heat through the plate which conforms to the needs of normal fiber laser light output efficiency of 70%–80%. The analytic value is in line with the changing trend of the experimental value, with the error of the temperature measurement points within ± 8.8%. The third segment rules out the influence of the optical fiber coupler location and the temperature of coupling point. When the pump power ranges from 4.4 W to 31.07 W, the error range between the experiment and analytics is within −4.14% to −0.82%. The layout plan of the fiber has a certain effect on the temperature uniformity of the fiber laser. It is demonstrated that the analytic method and mathematical assumption are reliable in the cooling design of the optical fiber.

1. Introduction

High power laser, with its high reliability, efficiency, and low cost characteristics, has a wide range of applications in communication and industry in recent years [1–3]. Making use of double clad fiber doped with rare earth ions is one of the advisable approaches to optimize the output power for single-mode fiber laser [4–6]. Several kilowatts of laser power output can be implemented by effectively coupling strong pump light source into the inner cladding. Continuous single-mode output power of 9.6 kW of single fiber by using all fiber main oscillation power amplification (MOPA) structure in 2009 has been reported [7].

The strong pump light source caused severe thermal dissipation when fiber laser used slender doped fiber as gain medium to realize several kilowatts of power output [8]. The reason is that the rising temperature in the doped fiber core will reduce quantum efficiency [9]. On the other hand, thermal stress from heat diffusion of host material [10] and the change of refractive index give rise to the thermal lens effect, and even the glass melting. According to the research [11] on optical fiber damage, the outer layer will be aging or even burn to lose its role, if the work temperature of outer cladding layer exceeds 80 °C, thus causing adverse impacts on the stability and lifetime of the fiber laser. It is shown that the problem of optical fiber cooling is extremely serious. As a consequence, effective cooling measures should be taken to reduce the thermal damage of high power fiber laser.

Many scholars have been engaged in solving fiber laser heat dissipation problems. S. Tokita et al. adopted a hybrid cooling mode, which combines water cooling in the length direction with convection cooling of fiber's end face on the erbium doped fiber ZBLAN that can effectively improve the stability of high power optical fiber [12]. L. Li et al. set a thermoelectric cooling device on the fiber and tried to use experimental methods to acquire the internal temperature distribution of high power fiber laser [13]. Simple cylindrical symmetry coordinates are usually adopted to obtain the temperature distribution inside the optical fiber [14,15]. Numerical simulations are used to study the multimode fiber or more complex fiber microstructure [14,16]. To a certain extent, these results depend on the accuracy of the boundary condition assumption and theoretical model. Thermal coupling simulations of the long fiber and cooling device are also limited by computing resources in the meantime. Experimental method needs ready-made device to obtain experimental data, and it is difficult to demonstrate the whole temperature field of the cooling system.

There is no simple and reliable thermal design method currently due

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Nomenclature

a, b, c, d	dimensions of the plate and heat source area, m
A	baseplate area, m^2
$A_0, A_1, A_2, A_3, B_0, B_1, B_2, B_3$	fourier coefficients
A_c	fiber core cross-section area, m^2
A_s	heat source area, m^2
$Error_{\bar{T}Ana-TExp}$	error between analytic value and experimental value, %
$Error_{\bar{T}Ana-\bar{T}Simu}$	error between analytic value and simulation value, %
h_l	heat transfer coefficient at lower surface of plate, W/(m^2·K) or W/(m^2·°C)
k_1	thermal conductivity of plate, W/(m·K) or W/(m·°C)
k_c	thermal conductivity of fiber core, W/(m·K) or W/(m·°C)
k_{in}	thermal conductivity of inner cladding layer, W/(m·K) or W/(m·°C)
k_{out}	thermal conductivity of outer cladding layer, W/(m·K) or W/(m·°C)
K_f	thermal conductivity of fiber, W/(m·K) or W/(m·°C)
L	length of fiber, m
m, n	indices for summations
N	number of heat sources
N_{dc}	doping concentration in the fiber core, m^{-3}
N_2	upper level population
P_p^l	forward pump power, W
P_p^r	backward pump power, W
$P_p^{\pm}(z_f)$	forward and backward pump power in the axis z_f, W
$P_s^{\pm}(z_f)$	forward and backward signal light power in the axis z_f, W
q	heat flux, W/m^2
Q	total power of heat source, W/m^3
$Q(z_f)$	heat power density in fiber in the axis z_f, W/m^3
r, z_f	coordinates used for fiber, m
r_1	fiber core radius, μm
r_2	inner cladding layer radius, μm
r_3	outer cladding layer radius, μm
R_1	reflectivity of the anterior cavity mirror
R_2	reflectivity of the posterior cavity mirror
R_{1D}	one dimensional thermal conductive resistance of plate, K/W or °C /W
R_{hl}	convective resistance for heat transfer coefficient h_l, K/W or °C /W
R_s	spreading thermal resistance, K/W or °C /W
R_{th}	thermal resistance, K/W or °C /W
R_{total}	total thermal resistance of network model, K/W or °C /W
t_1	thickness of plate, m
$T(x, y, z)$	plate temperature, K or °C
T_{Exp}	experimental temperature, K or °C
Tfa	free flow temperature or ambient temperature, K or °C
$\bar{T}_{Ana}$	average analytic temperature, K or °C
$\bar{T}_{Simu}$	average simulation temperature, K or °C
$\bar{T}_s$	average temperature of heat source, K or °C
$T(r, zf)$	temperature in fiber, K or °C
$\bar{T}_w$	average temperature of the lower wall, K or °C
x, y, z	coordinates used for plate, m
xc, yc	heat source centroid, m

Greek symbols

λ_p	pump wavelength, nm
λ_s	laser wavelength, nm
σ_{ap}	pump absorption cross-section, m^2
σ_{as}	signal absorption cross-section, m^2
σ_{ep}	pump emission cross-section, m^2
σ_{es}	signal emission cross-section, m^2
α_a	the absorption of pump light, m^{-1}
α_p	the loss of pump light, m^{-1}
Γ_p	pump power filling factor
Γ_s	laser power filling factor
β	eigenvalues, $\sqrt{\delta^2 + \lambda^2}$
δ	eigenvalues, nπ/b
λ	eigenvalues, mπ/a
φ	spreading function
ζ	dummy variable, m^{-1}
θ	temperature excess, $\equiv T - T_{fa}$, K or °C
ν_p	pump frequency
ν_s	signal frequency
τ	spontaneous lifetime
η	efficiency of absorption

Subscripts

1D	one-dimension
Ana	analytic
Exp	experimental
f	fiber
fa	ambient or cold source
i, j	indices for segment
l	lower surface
s	heat source
Simu	simulation

to the complexity of slender fiber itself, and such fiber thermal model is seldom available in the literature. Based on an example of 4.4–31.07 W ytterbium DDCF laser, this paper employs separation variable method to calculate spreading thermal resistance [17,18] of the eccentric heat sources on the rectangular channel and simulates the temperature field of the coupling of long fiber and substrate. This study focuses on the analysis of characteristics of optical fiber heat dissipation through the plate, and the results are verified experimentally.

2. Method and model

2.1. Heat source function

The simplified model of optical resonator sketch is shown in Fig. 1. Heat source of double clad fiber is generated due to the pump light absorbed by Y_b^{3+} doped in the fiber core. The length of fiber is much larger than the diameter of radial cross-section. Therefore, the thermal

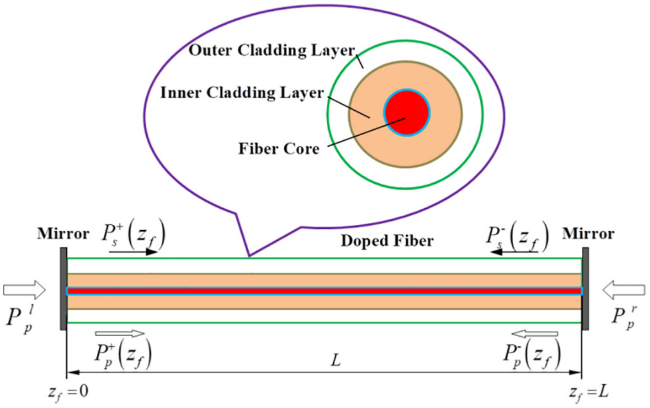

Fig. 1. Simplified model of optical resonator sketch.