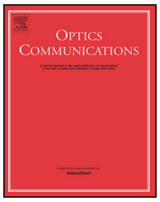
Optics Communications 419 (2018) 141–149

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom



Analytical thermal resistance model for high power double-clad fiber on rectangular plate with convective cooling at upper and lower surfaces

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ARTICLE INFO

Keywords:
Double-clad
Fiber
Convection heat transfer
Model
Verification

ABSTRACT

Whether convective heat transfer on the upper surface of the substrate is used or not, the thermal resistance network models of optical fiber embedded in the substrate are established in this research. These models are applied to calculate the heat dissipation in a high power ytterbium doped double-clad fiber (YDCF) power amplifier. Firstly, the temperature values of two points on the fiber are tested when there is no convective heat transfer on the upper surface. Then, the numerical simulation is used to verify the temperature change of the fiber with the effective convective heat transfer coefficient of the lower surface h_{eff} increasing when the upper surface is subjected to three loading conditions with h_u as 1, 5 and 15 W/(m^2 K), respectively. The axial temperature distribution of the optical fiber is also presented at four different values for h_u when h_{eff} is 30 W/(m^2 K). Absolute values of the relative errors are less than 7.08%. The results show that the analytical models can accurately calculate the temperature distribution of the optical fiber when the fiber is encapsulated into the substrate. The corresponding relationship is helpful to further optimize packaging design of the fiber cooling system.

1. Introduction

In terms of technology development, compared with the traditional CO_2 laser and solid laser, the fiber laser doped with rare earth elements [1] has many advantages, such as the beam quality, efficiency and heat dissipation. The fiber laser is also featured by easy industrialization with full fiber and compact structure. The fiber core, as lasing channels in the double-clad fiber [2], is made of quartz doped with materials such as ytterbium, thulium. The pump light reflects in the inner layer, traverses the fiber core, and is absorbed by doped elements, which is effectively converted into single mode laser [3]. The entire double-clad layer fiber adopts the structure of type D [3,4], as shown in Fig. 1(b), optical rotation effect of which is small, absorption is sufficient, and light-light conversion efficiency is more than 70% [4].

From previous studies, we know that the stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS) and thermal damage are major restrictions in the single fiber power of the fiber laser [1–11]. The beam quality is worsening with the output power increasing [5,6,11]. The approach of applying the large mode fiber and extending spectral bandwidth of the seed source can effectively reduce Brillouin scattering [7]. Similarly, the increase of fiber core diameter and the reduction of fiber length can weaken the stimulated Raman scattering [8]. Numerical computational studies of the maximum temperature in fiber and the average temperature in fiber laser design show that the heat in the optical fiber is harmful to the performance of the laser, especially when the ground state $^2F_{7/2}$ particles accumulate rapidly in the quasi-three-level fiber material Y_b: SiO_2 [6,9]. On one hand, the rising temperature in the doped fiber core [10–12] will reduce the quantum efficiency. On the other hand, both the thermal stress from the heat diffusion of the host material [6] and the change of refractive index contribute to the thermal lens effect [13], and even the glass melting. According to the work in reference [12] of optical fiber damage, if the surface of the fiber works under the temperature greater than 80 °C, the outer layer will be aging, even burn to lose its role, thus injuring the stability and service life of the fiber laser. Thus, effective cooling methods must be taken to reduce the thermal damage for high power fiber lasers.

Many scholars have studied heat dissipation problems of the fiber laser, and obtained the radial and axial temperature distributions of the fiber with heat conduction equations [3,13–16]. R. Weber et al. [13] applied numerical simulation and experimental method to compare the temperature and stress distributions of the fiber in four different water-cooled structures. Y. Wang [14] predicted that distributed pump

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https://doi.org/10.1016/j.optcom.2018.03.001
Received 21 September 2017; Received in revised form 9 February 2018; Accepted 1 March 2018

Nomenclature

a, b, c, d	Dimensions of the substrate and heat source, m
A	Substrate area, m^2
A_0, A_m, A_n, A_{mn}	Fourier coefficients
A_s	Heat source area, m^2
Ana_F, Ana_S	Analytical temperature, K or °C
$Error_{\bar{T}Ana-TExp}$	Error between analytical value and experimental value, %
$Error_{\bar{T}Ana-\bar{T}Simu}$	Error between analytical value and simulation value, %
h	Convection heat transfer coefficient, W/(m^2 K) or W/(m^2 °C)
h_{eff}	Effective convection heat transfer coefficient, W/(m^2 K) or W/(m^2 °C)
h_u	Heat transfer coefficient on upper surface of substrate, W/(m^2 K) or W/(m^2 °C)
h_l	Heat transfer coefficient on lower surface of substrate, W/(m^2 K) or W/(m^2 °C)
k_1	Thermal conductivity of substrate, W/(m K) or W/(m °C)
k_F	Thermal conductivity of fiber, W/(m K) or W/(m °C)
L	The length of double cladding fiber, m
m, n	Indices for summations
N	Number of heat sources
P_0	Pump power, W
$P\ (z_f)$	Power of the fiber axis z_f, W
q	Heat flux, W/m^2
Q	Total power of heat source, W
Q_1	Heat power density in fiber ,W/m
$Q\ (z_f)$	Heat power density of the fiber axis z_f , W/m^3
r, z_f	Coordinates used for the fiber, m
r_1	Fiber core radius, μm
r_2	Inner cladding layer radius, μm
r_3	Outer cladding layer radius, μm
R_{1D}	One-dimensional thermal conductive resistance of plate, K/W or °C/W
R_{heff}	Convective thermal resistance for heat transfer coefficient h_{eff}, K/W or °C/W
R_{hu}	Convective thermal resistance for heat transfer coefficient h_u, K/W or °C/W
R_s	Spreading thermal resistance, K/W or °C/W
R_{th}	Total thermal resistance, K/W or °C/W
$Simu_F, Simu_S$	Simulation temperature, K or °C
t_1, t_2	Thickness of upper board and lower board, m
T	Substrate temperature, K or °C
T_{Exp}	Experimental temperature, K or °C
T_{fa}	Free flow temperature or ambient temperature, K or °C
$\bar{T}_{Ana}$	Average analytical temperature, K or °C
$\bar{T}_{Simu}$	Average simulation temperature, K or °C
$\bar{T}_s$	Average temperature of heat source, K or °C
$T\ (r, z_f)$	Temperature in fiber, K or °C
$\bar{T}_w$	Average temperature of the lower wall, K or °C
x, y, z	Coordinates used for the substrate, m
x_c, y_c	Heat source centroid, m

Greek symbols

λ_p	Pump wavelength, nm
λ_s	Laser wavelength, nm
α_a	Pump absorption coefficient, m^{-1}
α_p	Scatting loss coefficient, m^{-1}
η	Absorbed part
β	Eigenvalues, $\sqrt{\delta^2 + \lambda^2}$
δ	Eigenvalues, $n\pi/b$
λ	Eigenvalues, $m\pi/a$
φ	Spreading function
ζ	Dummy variable, m^{-1}
θ	Temperature excess, $= T - T_f$, K or °C

Subscripts

1D	One-dimension
Ana	Analytical
Exp	Experimental
eff	Effective
f	Fiber
fa	Ambient or cold source
F	The first
i	Indices for segment
j	Indices for segment
l	Lower
S	The second
Simu	Simulation
u	Upper

structure can effectively dissipate the heat in the fiber and decrease the operating temperature without significantly reducing the laser output power. Fan et al. [16] added interface materials in three kinds of cooling grooves to reduce the thermal contact resistance between the fiber and heat sink. The temperature of the coupling point between tail fiber and active optical fiber is only 47 °C at bidirectional pump power of 1.26 KW.

Typically, heat flow encounters resistance when it enters into a small region of the system by conduction. Other than the thermal contact resistance, spreading thermal resistance is the main source of total thermal resistance in the electronics assembly. The thermal resistance of heating element is defined as [16]:

$$R_{th} = \frac{\bar{T}_s - T_{fa}}{Q} \tag{1}$$

where $\bar{T}_s$ is the average temperature of the heat source, T_{fa} is the ambient temperature, and Q is the dissipated heat of the heating device at steady state.

The spreading thermal resistance was obtained by analytical method and numerical simulation. The heat accumulated in light-emitting diodes (LED) would cause the deterioration of the output optical power, which was explained by Luo [17], revealing the mechanisms of the heat generation in chips in detail, and the importance of thermal resistance control in the process of LED package and application. Ma et al. [18] proposed a modified model of bidirectional thermal resistance to predict the junction temperature and phosphor temperature of LED. The thermal resistance model with the phosphor layer was established and measured in three kinds of LED packaging structures. A physical model was introduced to explain how package thermal resistance increases under constant cooling conditions by the work of Andrews [19]. After the application of electronic cooling, Feng and Xu [20] used the method of Fourier expansion to establish the three-dimensional spreading thermal resistance model for a cubic radiator. Muzychka et al. [21–26] investigated the spreading resistance characteristics of concentric and eccentric heat sources with the circular and rectangular systems in isotropic and anisotropic conditions.

In IC and LED packages, the examples mentioned above fall in the category of hot-spot issues due to the discrete features as the heat sources are usually very small compared to the size of the substrate. The fiber laser itself is complicated and it is continuously heating in the long fiber so that the slender fiber is different from ordinary hot-spot type heat sources. So far, there is no analytical model discussing the heat flow in the fiber packaging. Taking YDCF master oscillation