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Estimation of the Maximum Output Power of Double-Clad Photonic Crystal Fiber Laser *

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Compared with traditional optical fiber lasers, double-clad photonic crystal fiber (PCF) lasers have larger surface-area-to-volume ratios. With an increase of output power, thermal effects may severely restrict output power and deteriorate beam quality of fiber lasers. We utilize the heat-conduction equations to estimate the maximum output power of a double-clad PCF laser under natural-convection, air-cooling, and water-cooling conditions in terms of a certain surface-volume heat ratio of the PCF. The thermal effects hence define an upper power limit of double-clad PCF lasers when scaling output power.

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Recently, fiber lasers are one of the attractive fields of solid lasers and most works are focused on an increase of output power. In the past few years, the continuous output power of fiber lasers increased from hundreds of watts to kilowatts, and the average power of pulsed lasers is also hundreds of watts or more. In these fiber lasers, traditional doped double-clad silica fibers are currently used and the refractive index difference between the optical fiber clad and core is controlled using different dopants. Due to the single-mode requirement of waveguide structures, a small core-clad numerical aperture to maintain the single-mode transmission of the fiber leads to intense power density in a small core area, which hence brings strong nonlinear effects. The nonlinear effects, such as stimulated Raman scattering and stimulated Brillouin scattering, can limit the maximum output power of fiber lasers. Although some low nonlinear fibers have been developed and the output power can reach five hundred watts, further improving power is also challenging. Alternatively, one can eliminate nonlinear effects by reducing power density and shortening fiber length. An effective way is to use large-mode-area fibers. Large mode area will bring multimode propagation, which will lead to a restriction of most applications based on diffraction limited beam quality.

The use of photonic crystal fibers (PCFs) has provided a new way of constructing active optical devices since the 1990s, while overcoming the inherent contradiction between traditional fiber laser theories and actual needs of high output power. Different from the traditional optical fibers, light is controlled by a small array of clad air holes along the axial direction in PCFs. The outer clad of the double-clad structure in PCFs is made of silicon nets, and the width of net is less than the transmission wavelength. This kind of design of outer clad can reduce the inner clad diameter. The inner clad of double-clad structure in PCFs is periodic air holes. Refractive index of the porous region is lower than the surrounded solid area. This kind of structure will bring single-mode waveguides. The core of PCFs is a rare earth dopant. Large-mode-area, large numerical aperture and endless single-mode transmission characteristics can be realized in a double clad structure by designing positions of air holes in PCFs. A high rare earth dopant can effectively reduce the length of fibers. All the above-mentioned factors can effectively reduce the nonlinear effects. Low nonlinear effects can solve the problems of the thermal effects and maintain good beam quality[1] when lasers work at high output power. Thus double clad PCFs are a revolutionary breakthrough in the fiber laser technology field. These characteristics essentially solve the problems of traditional fiber lasers, which show new broad prospects of market applications.[2]

Because of thermal lensing and the thermally induced birefringence effect, bad beam quality will occur during high output power. Heat energy from non-radiation transition is also dangerous to high power lasers. In order to obtain a good laser beam, we must dissipate the heat energy in the laser gain medium. Thus we need to solve the cooling problem of double clad PCF lasers. Fibers are gain media of fiber lasers. Their elongated shapes can make a high ratio of surface area to volume. High surface-area-to-volume ratio can increase the cooling area in favor of solving the solid-state laser radiating heat problem. Double clad PCFs are better than traditional single-mode fibers at surface-area-to-volume ratio. Thus double clad PCFs are suitable for high and superhigh power lasers. Yb^{3+} doped double clad fibers are the best choice of high power fiber laser or amplifier in view of quantum conversion efficiency, damage threshold and substrate loss, especially high surface-area-to-volume ratio. The output power of a double clad PCF laser rises stage by stage, and continuous output power has been achieved kW under cooling conditions.

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Compared with traditional optical fiber lasers, double clad PCF lasers have a large surface-area-to-volume ratio.[3] When they work at low power, they can effectively dissipate heat energy. With output power increasing, the thermal effect will seriously restrict the output power of fiber lasers and reduce beam quality. Therefore the thermal effect[4] of high power PCF laser should be considered. Thus the cooling problem of double clad PCF lasers is very important.

Next, we give a theoretical estimation of cooling of a double clad PCF laser. Preferably the temperature is below 80℃ of the acrylic[5] of the optical fiber coating. When temperature is greater than 80℃, the PCF laser will gradually age and blacken, thus losing the protective effect of the inner layer. Thus the PCF laser in a high power running condition must have an appropriate type of cooling to keep the coating temperature below 80℃. If the critical temperature is 80℃ of the coating, we will estimate the output power of the double clad PCF lasers under natural convection, air cooling and water cooling conditions.

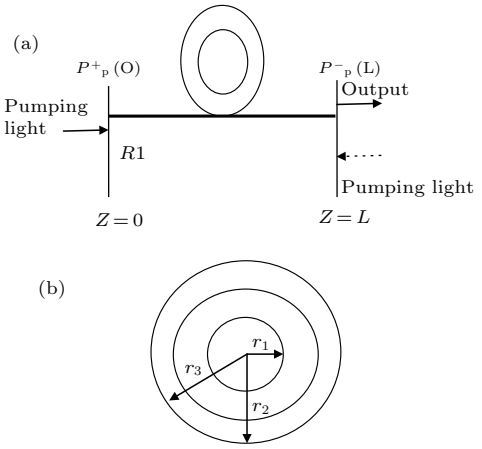


Fig. 1. (a) Bi-directionally pumped double-clad fiber laser and (b) fiber cross section.

The schematic diagram of the bi-directionally pumped PCF fiber laser is shown in Fig. 1(a), $P_{\rm p}^{+}(0)$ and $P_{\rm p}^{-}(L)$ are the pump powers at the front and back ends, R_1 and R_2 are the signal light reflectivities of the fiber end-face. In order to simplify the calculation, we can take various shapes of the inner clad equivalent to a circular inner clad layer, such as shown in Fig. 1(b), r_1, r_2 and r_3 are denoted the radii of the double clad optical fiber core, the inner clad layer and the outer clad layer. We can describe the heat effect by the classical heat transfer equation in high power optical fiber lasers. Consider that heat is only in the fiber core and radial distribution is Gauss distribution[6] without heat in the clad region. The fiber core and inner clad layer are silica, so the conductivities of the core and the inner clad layer are equal to each other, denoted by k_1. The outer layer is a polymer material, its thermal conductivity (denoted as k_2) smaller than silica.

Doped ions in the inner core absorb pump energy by the role of the heat source function $Q(r,z)$, and at the same time, it is equivalent to one clad based on no heat source of the inside and outside clads. The steady state heat conduction equation,[7] because longitudinal heat conduction in the laser medium affects a very small area near or at the pumping face, reads

$$\begin{aligned}&\frac{1}{r}\frac{\partial}{\partial r}\Big(r\frac{\partial T_1(r,z)}{\partial r}\Big)=-\frac{Q(r,z)}{k},\quad 0\le r\le r_1,\\&\frac{1}{r}\frac{\partial}{\partial r}\Big(r\frac{\partial T_2(r,z)}{\partial r}\Big)=0,\quad r_1\le r\le r_3,\end{aligned}\tag{1}$$

where r is the distance of any point of fiber to the center axle z, and k is a thermal conductivity. T_1 and T_2 are core and clad region temperature. Temperature boundary and temperature derivative of the continuity follow

$$\frac{\partial T_1}{\partial r}=0,\ T_1|_{r=r_1}=T_2|_{r=r_1},\ \frac{\partial T_1}{\partial r}|_{r=r_1}=\frac{\partial T_2}{\partial r}|_{r=r_1}.\tag{2}$$

The optical fiber clad surface is described by Newton's law of cooling,

$$\frac{\partial T_2}{\partial r}|_{r=r_3}=\frac{h}{k}(T_0-T_2|_{r=r_3}),\tag{3}$$

where h is denoted as the convective heat transfer coefficient, and T_0 is room temperature. The core of heat source function is the Gauss type[8] because of a semiconductor laser used as the pump source, in the two-directions pump case,

$$Q(r,z)=\frac{2a\eta_{\rm h}P_{\rm p}(z)}{\pi\omega_{\rm p}^2}\exp(-2r^2/\omega_{\rm p}^2),\tag{4}$$

where $P_{\rm p}(z)=P_{\rm p}^{+}(z)+P_{\rm p}^{-}(z)=P_{\rm p}^{+}(0)\exp(-az)+P_{\rm p}^{-}(L)\exp[-a(L-z)]$ represents the sum total power of the forward and reverse transmission pump light at optical fiber z point; L is length of fiber, and a is total loss of pump light including absorption loss ($a_{\rm a}$) and scattering loss ($a_{\rm s}$); $\eta_{\rm h}$ is heat transfer coefficient, and $\omega_{\rm p}$ is pump Gauss radius. If pump light is coupled into the fiber core, $\omega_{\rm p}$ is approximately the fiber core radius r_1. Substituting Eq. (4) into the heat conduction equation (1) and boundary condition (3), we can obtain the analytic solution double-clad fiber laser temperature distribution,

$$\begin{aligned}T_1=&T_{\rm h}+\frac{a_{\rm s}\eta_{\rm h}P_{\rm p}(z)}{2\pi k}\sum_{m=1}^{\infty}\frac{(-1)^m}{m!}\Big[\frac{(r/r_1)^{2m}-1}{m}\\&+2\ln\Big(\frac{r_1}{r_2}\Big)-\frac{2k}{hr_2}\Big],\quad 0\le r\le r_1,\\T_2=&T_{\rm h}+\frac{a_{\rm s}\eta_{\rm h}P_{\rm p}(z)}{2\pi k}\sum_{m=1}^{\infty}\frac{(-1)^m2^m}{m!}\Big[\ln\Big(\frac{r_1}{r_2}\Big)-\frac{k}{hr_2}\Big],\\&r_1\le r\le r_3.\end{aligned}\tag{5}$$

The parameters, based on ordinary Yb^{3+} doped double-clad fiber, are as follows: $P_{\rm p}^{+}(0)=500\,{\rm W}$, $P_{\rm p}^{-}(L)=500\,{\rm W}$, $\lambda_{\rm p}=976\,{\rm nm}$, $\eta_{\rm h}=0.1012$, $a=1.4\times10^{-3}\,{\rm cm}^{-1}$, $L=20\,{\rm m}$, $r_1=10\,\mu{\rm m}$, $r_2=200\,\mu{\rm m}$, $r_3=280\,\mu{\rm m}$, $h=10\,{\rm W\cdot m^{-2}K^{-1}}$, $k=1.38\,{\rm W\cdot m^{-2}K^{-1}}$.

We can obtain that the axial temperature range changes more, but the radial temperature changes less.

Without active cooling of lasers, in the case of surface free convection heat transfer, the free convection heat transfer coefficient is typically $10\,\mathrm{W{\cdot}m^{-2}K^{-1}}$. When the out-source layers of temperature is 80℃, pumping energy distribution is mostly near the end two faces. For faster temperature rising following the absorption of the energy, the maximum of output power of the ordinary double-clad fiber laser is 105 W. In the air cooled case, corresponding to the surface of free convection heat transfer coefficient $10{:}80\,\mathrm{W{\cdot}m^{-2}K^{-1}}$, the maximum output power of the ordinary double-clad fiber is 105–820 W. In order to obtain the output power above kW of fiber laser, we must further increase the convection heat transfer coefficient of the optical fiber surface through actively cooled water. The speed of water directly determines the convection heat transfer coefficient of the optical fiber surface in the water-cooled case. The convection heat transfer coefficient will be $300{:}1000\,\mathrm{W{\cdot}m^{-2}K^{-1}}$ in the corresponding compulsory water-cooled case. With 80℃ at the critical point of the surface temperature of the fiber, theoretically the corresponding convective heat transfer coefficient is $1000\,\mathrm{W{\cdot}m^{-2}K^{-1}}$, so the maximum output power of the optical fiber can reach 8.8 kW.

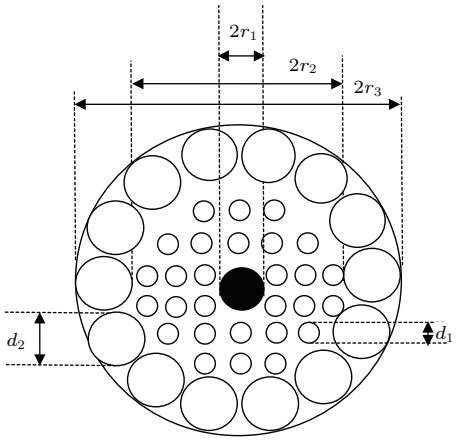


Fig. 2. Cross section of the DPFL.

Define surface-volume heat ratio as the product of surface area and heat conductivity coefficient divided by the product of density and volume. Differences of heat conducting performance between normal double-clad fiber and double-clad PCF are given by

$$P = \frac{\sum_i k_i s_i}{\sum_j \rho_j V_j}. \tag{6}$$

As shown in Fig. 2, the surface-volume heat ratio reads, corresponding to double-clad optical fiber core radius r_1, inner clad radius r_2 and clad radius r_3,

$$\Pi_{\mathrm{p}} = \frac{k_1 r_1 + (k_1 + k_2) r_2 + k_3 r_3}{(\rho_1 - \rho_2) r_1^2 + (\rho_2 - \rho_3) r_2^2 + \rho_3 r_3^2}. \tag{7}$$

If it is assumed that core radius r_1, inner clad radius r_2, clad radius r_3, inner and outer clad of double-clad PCF are of quartz materials, where the inner clad radius is d_1, the hole number density in the inner clad is n_1, the outer clad radius is d_2, the hole number density in the outer clad is n_2, as shown in Fig. 2, the corresponding surface-volume heat ratio is $n_1 d_1^2 + n_2 d_2^2 \approx r_3^2 - r_1^2$,

$$\Pi_g = \frac{k_1 r_1 + (k_1 + k_2) r_2 + k_2 r_3 + k_2 (d_1 n_1 + d_2 n_2)}{(\rho_1 - \rho_2) r_1^2 + \rho_2 r_2^2}. \tag{8}$$

The surface-volume heat ratio increases with increasing d_1, n_1, d_2, n_2 as expressed by Eq. (8). Given $r_1 = 10\,\mu\mathrm{m}$, $r_2 = 200\,\mu\mathrm{m}$, $r_3 = 280\,\mu\mathrm{m}$, $d_1 = 0.6\,\mu\mathrm{m}$, $d_2 = 11\,\mu\mathrm{m}$, $n_1 = 162$, $n_2 = 73$, the surface-volume heat ratio of the double-clad PCF will be enlarged by 2–3 orders more than the typical double clad. Based on the above deducing, the maximum output power of the double-clad PCF will reach 8.8×10^2–8.8×10^3 kW at 80℃ critical point of surface temperature with convective heat transfer coefficient 10–$1000\,\mathrm{W{\cdot}m^{-2}K^{-1}}$ in water cooled cases. The possible perspective of rising power of the double-clad PCF laser will be of megawatts based on the limit of heating effects.

In summary, the heat-conduction equation is used under the natural convection and under air-cooling and water-cooling conditions. The thermal effects hence define an upper power limit of double-clad PCF lasers when scaling output power. We estimate the limit of output power of double-clad PCF lasers to megawatts.

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