TuA4.6
5:15 pm – 5:30 pm

# Power capacity of hollow Bragg fibers, CW and pulsed sources.

M. Skorobogatiy, Steven A. Jacobs, Steven G. Johnson, O. Weisberg, Torkel D. Engeness, Yoel Fink

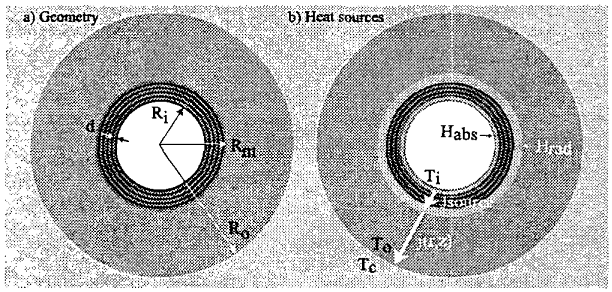


Fig. 1. Power capacity analysis of a hollow Bragg fiber. (a) Schematic of a fiber. Hollow core of radius $R_i$, mirror region of $N$ bilayers each of thickness $d$ surrounded by an over-cladding extending to $R_o$. (b) Two major types of heat sources (shown in light gray) - $H_{abs}$ is due to a field penetration and absorption in the mirror region, $H_{rad}$ is due to the radiation leakage through a finite size mirror and absorption in the over-cladding.

Large-core hollow dielectric fibers have been recently investigated to provide a guiding platform for high power radiation in a wide range of IR frequencies [1–3]. Due to the absence of an absorbing material in the core, hollow fibers have been demonstrated to guide kilowatts of CW power at a designable IR wavelength. The power capacity of these fibers is limited by the maximum temperature that a fiber material can withstand before damaged. In this paper, we investigate the power capacity and failure mechanisms for an emerging new type of high power radiation guides—hollow photonic Bragg fibers (PBF). CW and pulsed radiation sources are considered, assuming continuous operation of the laser source.

Hollow Bragg fiber consists of a hollow core, a series of bilayers of contrasting refractive-index glasses and an over-cladding. Figure 1a illustrates the schematic cross section of PBF. The hollow-core radius is $R_i$ and the dielectric mirror has $N$ bilayers extending to a radius $R_m$. Each bilayer has a thickness $d$. The outer radius of the over-cladding is $R_o$. Typically, $R_i \sim R_m \ll R_o$. The electromagnetic field decays exponentially in the mirror. Thus, field penetration into the mirror is largely limited to the first few bilayers. Since the core area that transmits most of the light is several orders of magnitude larger than the mirror area, power dissipation due to material absorption $H_{abs}$ is greatly suppressed, with most heating happening in the first few mirror layers (shown in light gray on Figure 1b). Another mechanism of power dissipation in PBFs is radiation $H_{rad}$ leaking through the finite-size mirror. Most of such radiation is converted to heat in the over-cladding region. As the over-cladding absorption is very high (as high as $10^5\ \frac{dB}{m}$), typically, all heat conversion occurs in a thin circular region at $R_m$ just outside the mirror (shown in light gray on Figure 1b). If there is no gas flow through the core, heat transfer to the core is almost nonexistent. Therefore, all heat dissipation occurs through the over-cladding periphery at $R_o$. Cooling there is provided by conduction and convection to gas or flowing water at an operating temperature $T_c$. Heat transfer from fiber to coolant is characterized by a heat transfer coefficient $h$, where for dry air $h = 5\ \frac{W}{m^2K}$, forced dry air $h = 25\ \frac{W}{m^2K}$, and water $h = 200\ \frac{W}{m^2K}$.

Contact e-mail: maksim@omni-guide.com
OmniGuide Communications, One Kendall Square, Building 100, Cambridge MA 02139

A typical design for $\lambda = 10.6\ \mu m$ has $R_i = 500\ \mu m$, $R_o = 1500\ \mu m$. The mirror materials can be chosen to be a polymer (low index) and chalcogenide glass (high index) with indices of $n_l = 1.5$ and $n_h = 2.8$ respectively, and a bilayer thickness $d = 3\ \mu m$ with 14 bilayers total. The intrinsic bulk absorption losses of the high index material are $\sim 10\ \frac{dB}{m}$, an overestimate for high-purity chalcogenide glasses at $10.6\ \mu m$. The over-cladding and low index material are assumed to have absorption losses of $10^5\ \frac{dB}{m}$, a value typical for polymers. These material parameters yield a total $HE_{11}$ modal loss of $\alpha_{HE_{11}} \sim 0.1\ \frac{dB}{m}$. For this design, total power dissipation is dominated by material absorption losses in the first few layers of the mirror.

For a given propagating mode, the equilibrium temperature profile can be found by solving a standard heat transfer equation with sources determined by the modal profile in the absorbing regions of a fiber. We find that solution of the heat equation with exact sources can be approximated very well by a simpler model. Instead of an exact heat source, we assume a thin circular heat source ($H_{abs}+H_{rad}$) at $R_i$ such that $j_r(r,z)|_{r=R_i} = P_m \alpha_m exp(-\alpha_m z)$, where $P_m$ is the partial power and $\alpha_m$ is the loss of the mode $m$. Boundary conditions also assume a zero heat flux through the ends and into the core of a fiber $j_z(r,z)|_{z=0} = j_z(r,z)|_{z=L} = 0$, where $L$ is the length of a fiber. Finally the heat flux to the coolant is assumed as $j_r(r,z)|_{r=R_o} = h(T(r,z)|_{r=R_o} - T_c)$.

We first analyze the heating of PBF transmitting a power $P_{av}$ from a CW laser source. For CW sources, the temperature rise in a fiber is very sensitive to the cooling conditions, with most of the temperature rise occurring at the over-cladding's coolant interface, and only a small temperature difference across the fiber cross-section. We assume laser beam coupling to the fiber modes labelled by index $m$ with fractional powers $P_m$ in each of them, and that $k = 0.25\ \frac{W}{mK}$ is a heat conductance of the over-cladding. The hottest region in the fiber is at the coupling facet of the fiber, near the inner mirror edge, with a temperature rise $\Delta T = T_i - T_c$ given by

$$\Delta T \approx \sum_{R_i\alpha_m \ll 1} P_{av}^m \alpha_m \left(\frac{1}{2\pi R_o h} + \frac{\log(R_o/R_i)}{2\pi k}\right) + \sum_{R_i\alpha_m \gg 1} P_{av}^m \left(\frac{2\log(\alpha_m R_i)}{\pi^2 R_i k}\right) \quad (1)$$

The first summation in the above equation accounts for the core guided modes, each of which have relatively small modal losses and modal decay occurring on a length scale larger than the core radius: $R_i\alpha_m \ll 1$. These modes are relatively benign because heating from dissipation of such modes can be counteracted by improved cooling. When coupling to these fiber modes, one has to avoid coupling to the very lossy over-cladding modes $R_i\alpha_m \gg 1$, for which all the power is immediately converted into heat in a small spatially localized region near the input fiber facet. Heating from such modes can not be effectively counteracted, as the heated region is smaller than the fiber cross-section, rendering heat dissipation through the outer boundary ineffective. We find that the optimal coupling is $P_{HE_{11}} \sim 98\%$ of power from the Gaussian laser beam to the $HE_{11}$ mode of a fiber, achieved when the diameter of the laser beam is $\sim 0.6$ times the fiber diameter, with coupling to the very lossy over-cladding modes being $P_{clad} \sim 10^{-3}$. Choosing a laser beam diameter smaller than the optimal, while reducing coupling to the $HE_{11}$ mode, also greatly reduces the coupling to the over-cladding modes, with the rest of the power going to the relatively low-loss core-guided modes. Thus, with a laser beam diameter of 0.3 times the core diameter, power in the $HE_{11}$ mode is still $P_{HE_{11}} \sim 65\%$ while power in the over-cladding modes is less than $P_{clad} \sim 10^{-6}$. Thus, using smaller-waist laser beams at the coupling facet of the fiber can substantially reduce fiber heating in expense to a certain deterioration of the beam quality.

We now analyze the heating of a PBF transmitting radiation coming from a pulsed source. We assume a $P_{av}$ average power being transmitted through a fiber with $\tau$ pulse duration and $\nu$ repetition rate. We define $P_{pk}$ to be the peak transmitted power $P_{pk} = \frac{P_{av}}{\tau\nu}$. In practical applications, pulse duration is much smaller than the characteristic temperature equilibration time across the fiber cross-section $\tau_{eq} = C_v R_i^2/k \approx 1\ s$, where heat capacity of the over-cladding is $C_v = 10^6\ \frac{J}{m^3 K}$. In such a regime of short pulses, the temperature distribution across the fiber cross-section will be modified from that of the equilibrium distribution corresponding to the average transmitted power $P_{av}$ given by (1). In general, power handling of pulsed radiation is worse than power handling of CW radiation for the same average power. Physically, this can be attributed to the excitation of time dependent source of localized "heat waves." The shorter the duration of the pulse, the more localized the "heat wave," which greatly reduces the heat exchange through the outer boundary of the fiber to the coolant. For the very lossy over-cladding modes, heating becomes even more problematic because of the additional localization of the heat in the direction of propagation due to a very rapid modal decay. Special care should be taken to reduce coupling to the over-cladding modes. The hottest region of

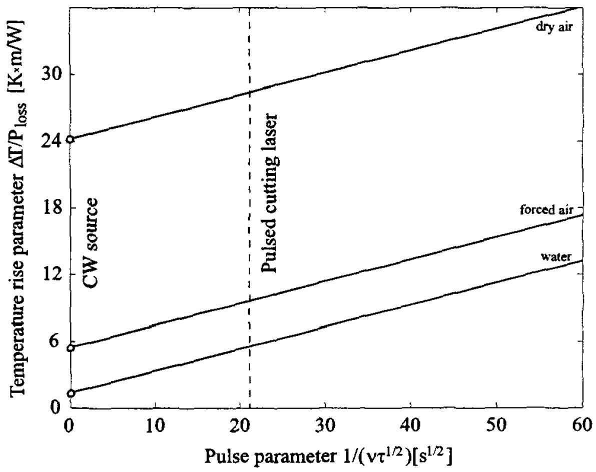


Fig. 2. Temperature rise parameter curves as a function of a laser pulse parameter, $\nu$ - pulse repetition rate, $\tau$ - pulse duration. Different curves correspond to the different cooling mechanisms.

the fiber will be at the coupling facet of the fiber near the inner core radius. Peak temperature values in this region over time can be found by solving the time-dependent heat transfer equation with the abovementioned flux boundary conditions. Assuming a repeated Gaussian pulse such that $\tau \ll \frac{1}{\nu} \ll \tau_{eq}$ we get

$$\Delta T \approx \sum_{R_i\alpha_m \ll 1} P_{av}^m \alpha_m \left(\frac{1}{2\pi R_o h} + \frac{\log(R_o/R_i)}{2\pi k} + \frac{1}{2\pi k(\nu\sqrt{\tau_{eq}\tau})}\right) + \sum_{R_i\alpha_m \gg 1} P_{av}^m \left(\frac{2\log(\alpha_m R_i)}{\pi^2 k R_i} + \frac{\log\left(\alpha_m R_i\sqrt{\frac{\tau}{\tau_{eq}}}\right)}{2\pi k(\nu\tau R_i)}\right) \quad (2)$$

Assuming that high-loss over-cladding modes ($R_i\alpha_m \gg 1$) are suppressed, for a given fiber design, the temperature rise for the pulsed source (2) as a function of the average power, pulse duration and pulse repetition rate can be presented by a universal curve in the coordinates $(\frac{\Delta T}{P_{loss}}, \frac{1}{\nu\sqrt{\tau}})$, where $P_{loss} = \sum_{R_i\alpha_m \ll 1} P_{av}^m \alpha_m$. In these coordinates, the temperature rise is given by a family of straight lines (Figure 2) each corresponding to a different cooling mechanism. From (1), we see that the CW power capacity is shown on Figure 2 at $\frac{1}{\nu\sqrt{\tau}} = 0$. In the current design, for example, and a temperature rise of $\Delta T = 150\ K$, dry air cooling, and an $HE_{11}$ mode of operation defines a CW power capacity of $P_{av}^{max} = 300\ W$. For a cutting laser with $\tau = 200\ ns$ and $\nu = 100\ Hz$, the maximum power capacity is $P_{av}^{max} = 150\ W$ with $P_{peak}^{max} = 10^6\ W$.

## References

[1] J. Dai, and J.A. Harrington, Applied Optics, **36**, 5072 (1997).

[2] S.S. Sato, H. Ashida, T. Arai, Y.W. Shi, Y. Matsuura, and M. Myagi, Optics Letters, **25**, 49 (2000).

[3] B. Temelkuran, S.D. Hart, G. Benoit, J.D. Joannopoulos, and Y. Fink, Nature, **420**, 650 (2002).