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# Fiber Fuse Simulation in Double-Clad Fibers for High-Power Fiber Lasers

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**Abstract:** Rare-earth-doped optical fibers are one of the most promising solid-state lasers. In these fiber lasers, a cladding-pumping scheme using double-clad fibers is utilized to increase the overall conversion efficiency of pumping light. To maintain acceptable beam quality, the low-numerical aperture large-mode-area fibers is effective for the double-clad fibers because the effects of stimulated Raman scattering can be reduced via the corresponding reduction in the power density in the large fiber core. For the large-mode-area double-clad fibers, fiber fuse propagation was investigated theoretically by the explicit finite-difference method using the thermochemical $SiO_x$ production model. In the calculation, we assumed the fiber to be in an atmosphere and that part (40 µm in length) of the core was heated to a temperature of 2,923 K. The threshold power for the double-clad fiber with the core radius of 10 µm was 1.6 W at 1.080 µm and it was close to the experimental value. The power dependence of the velocity of fiber fuse propagation was calculated for the double-clad fibers with the core radius of 10 and 15 µm. The calculated velocities were in fair agreement with the experimental values observed in the input power range from 1 kW to 3.5 kW at 1.080 µm.

**Keywords:** Fiber Laser, Fiber Fuse Phenomenon, Double-Clad Fiber, Finite-Difference Technique

## 1. Introduction

Rare-earth-doped optical fibers are one of the most promising solid-state lasers for efficient diode-pumped high power continuous-wave (CW) and fiber chirped-pulse amplification (CPA) laser systems. The output power from the ytterbium (Yb)-doped fiber lasers has abruptly increased over the past decade [1-6]. CW laser oscillation in a Yb-doped single-mode optical fiber was first observed by Hanna *et al.* in 1988 [7]. Extensive work on laser operation of $Yb^{3+}$ ion in silica fibers was reported by several research institutes [8-14]. An attractive feature of $Yb^{3+}$-doped silica fiber is that it provides a very broad fluorescence in the 1 µm region without excited-state absorption thus offering the potential of broadly tunable laser operation. Hanna *et al.* reported smooth continuous tuning from 1.010 µm to 1.162 µm, but only with low output powers of < 20 mW [9].

The simplicity of the energy level structure of $Yb^{3+}$ gives freedom from excited-state absorption, concentration quenching, and multiphoton nonradiative decay [13, 14]. These features combined with small energy defect between pumping and emission photons allow highly efficient conversion from the absorbed photons.

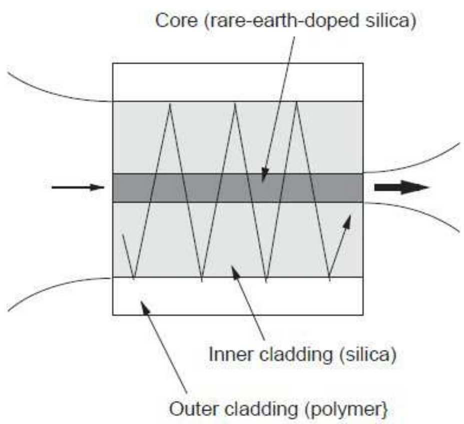


***Figure 1.*** *Schematic of cladding pumping in the DCF.*

The overall conversion efficiencies are limited by the launch efficiency of the pump beam into the single-mode fiber core, and high conversion efficiencies (about 70% [13])

from 0.975 μm pump light are obtained in $Yb^{3+}$-doped silica fiber by using a cladding-pumping scheme [15] to ensure that virtually all of the incident pump power is absorbed in the doped fiber core.

The cladding-pumping scheme can be realized using double-clad fibers (DCFs), as shown in Figure 1. In a double-clad configuration, light focused into the inner cladding is absorbed by the $Yb^{3+}$-doped fiber core as the pump light proceeds down the fiber. This allows the use of multimode pump sources and relatively simple focusing systems for efficient coupling. High output power of 500 mW for 0.975 μm pump light was obtained by Pask *et al*. in 1994 using a cladding-pumped $Yb^{3+}$-doped DCF [13]. Higher power DCFs have also been reported by several research institutes [16-20].

Diffraction-limited beam quality from Yb-doped fiber laser with 135 W output power was demonstrated by Platonov *et al*. who used DCFs with relatively small core diameter of 9 μm [20]. They found that the output power was limited by the onset of stimulated Raman scattering. To overcome this restriction, the concept of low-numerical aperture large-mode-area (LMA) fibers [21, 22] is effective because the effects of Raman scattering can be reduced via the corresponding reduction in the power density in the large fiber core. With regard to optical damage to the end faces, a large-core design is preferred while maintaining acceptable beam quality. The core diameter needed to maintain single-mode transmission depends on a numerical aperture (NA); the smaller the NA, the larger the diameter of a core that could support single-mode transmission. Typical LMA fibers used in the CW laser operation have core diameters of 20-40 μm and an NA of < 0.09 [23-27]. High output power of > 200 W in the CW laser operation has been reported using cladding-pumped Yb-doped and/or Nd+Yb-doped LMA fibers [23-40].

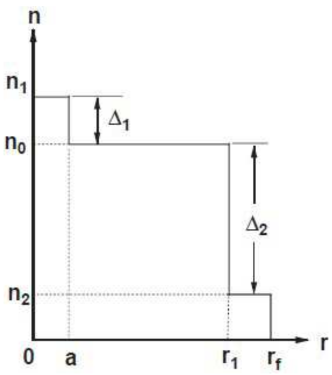


***Figure 2.*** *Refractive-index profile of a DCF.*

On the other hand, it is extremely challenging to increase the fiber core size while retaining the excellent beam quality because fibers with large core size allow propagation of several transversal modes, except for the fundamental mode (FM). As a result, the beam quality of these fibers is influenced by the existence of a higher-order mode (HOM). Wirth *et al.* reported the generation of 1,250 W of narrow linewidth (80 pm) nearly diffraction-limited radiation by a Yb-doped photonic crystal fiber amplifier [41]. They found that the beam quality factor $M^2$ was about 1.3 and below for output power level up to approximately 1,250 W, and then it increased rapidly to large values of 1.85-1.95 at power level above 1,250 W. It was found that a degradation of beam quality above threshold power (1,250 W) was responsible to superposition of the HOM ($LP_{11}$ mode) on the FM ($LP_{01}$ mode) [41].

This phenomenon of transverse mode instability (TMI) was observed in many fiber lasers and amplifiers under CW and pulsed-pump mode of operation [33, 34, 42-61]. It causes the output beam profile fluctuations in a seemingly chaotic way between the FM and one (or more) HOM.

Although the exact mechanism ultimately causing the energy transfer between the FM and HOM and dynamic behavior of the beam fluctuations is still under discussion, a (quasi-static) thermally-induced index grating [62-64] is the most plausible explanation for the TMI. Recently, Jauregui *et al*. have proposed a novel technique for stabilizing the output beam of a fiber laser system operating above the mode instability threshold [58]. This technique, which relies on a modulation of the pump power, can wash out the thermally-induced refractive index gratings and improve power and beam stability at powers up to twice the normal threshold for onset of the instability [58].

One of the problems other than the TMI arising from high power injection in Yb-doped DCFs is the probability of detonating the fiber fuse effect. In this article, we describe the results of some numerical calculations related to the fiber fuse effects in the DCFs for high-power fiber lasers.

# 2. Fiber Fuse Effect in DCFs

The first fiber fuse ignition was observed in an Yb-doped DCF with a core radius $a$~5.25 μm by Wang *et al.* in 2008 [65] and then the fiber fuse effect was observed in a Er-doped fiber [66] and Yb-doped bismuthate glass waveguide laser [67].

Recently, several fiber fuse experiments have been conducted on the Yb-doped DCFs for high-power fiber lasers by Zhang *et al.* ($a$ = 15 μm) at 1.064 μm [68], Sun *et al.* ($a$ = 10 and 15 μm) and Xiao *et al.* ($a$ = 10 μm) at 1.080 μm [69, 70], respectively.

### *2.1. Parameters of DCFs*

The refractive-index profile of the DCFs used by Zhang *et al.*, Sun *et al.*, and Xiao *et al.* is shown in Figure 2. In this figure, $n_0$, $n_1$ and $n_2$ are the refractive indices in the core, inner cladding, and outer cladding, respectively. The relative refractive-index differences $\Delta_1$ and $\Delta_2$ are defined as

$$\Delta_1 = \frac{(n_1^2 - n_0^2)}{2n_1^2} \sim \frac{(n_1 - n_0)}{n_1} \quad (1)$$

$$\Delta_2 = \frac{(n_0^2 - n_2^2)}{2n_0^2} \sim \frac{(n_0 - n_2)}{n_0} \quad (2)$$

The DCFs have a 20-30-μm-diameter Yb-doped silica glass core, a 400-μm-diameter inner cladding, and a 500-μm-diameter outer cladding consisting of a low- refractive-index polymer [68, 70]. Furthermore, Jeong *et al.* reported that the NA (= $n_1\sqrt{2\Delta_1}$) of the core is very small (< 0.05) and the NA (= $n_0\sqrt{2\Delta_2}$) of the inner cladding is 0.48 [27]. From these NA values, we estimated $\Delta_1$ to be smaller than 0.05% and $\Delta_2$ ~5.5%.

The parameters of the DCFs used in the fiber fuse calculation are shown in Table 1.

***Table 1.*** *Parameters of the DCFs.*

| Parameters | Unit | DCF10 | DCF15 |
|---|---|---|---|
| $\Delta_1$ | % | 0.030 | 0.013 |
| $\Delta_2$ | % | 5.50 | 5.50 |
| $a$ | μm | 10 | 15 |
| $r_1$ | μm | 200 | 200 |
| $r_f$ | μm | 250 | 250 |
| $A_{eff}$ | μm$^2$ | 477 | 1,097 |

In the following, the DCFs with $a$ = 10 and 15 μm are referred to as DCF10 and DCF15, respectively.

In this table, $A_{eff}$ is the effective cross-sectional area at the wavelength $\lambda_0$ = 1.080 μm defined as

$$A_{eff} = \pi\omega^2 \quad (3)$$

where ω is the mode field radius at $\lambda_0$. This ω is defined as [71]

$$\frac{\omega}{a} = 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \quad (4)$$

where $V$ is the normalized frequency of the optical fiber. $V$ is given by

$$V = 2\pi a\, n_1\sqrt{2\Delta_1}\ /\ \lambda_0 \quad (5)$$

### *2.2. Fiber Fuse Initiation in DCFs*

Fiber fuse was observed in Yb-doped DCFs operated in a master oscillator power amplifier (MOPA) configuration [65, 68-70]. Wang *et al.* reported that the fiber fuse was initiated at the fiber end surface through physically adhered wet-alumina particles and/or the clusters of them interacting with high-power laser light in the core region [65]. Xiao *et al.* prepared an initiation point on a section of DCF near the output end where the polymer coating (outer cladding) was removed, and a piece of metal as absorptive material was manually put on the exposed inner cladding. The fiber fuse was initiated at this point when the maximum power of 3 kW passed through the point [70]. In these cases, it was considered that fiber fuse was generated in the Yb-doped core layer owing to thermally decomposition of $SiO_2$ (accordingly thermochemical $SiO_x$ production) [65, 70].

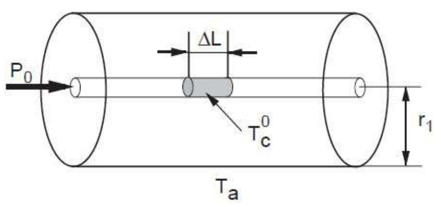


***Figure 3.*** *Schematic view of the hot zone in the core layer.*

In the following subsection, we describe the unsteady-state thermal conduction process in the DCFs theoretically by the explicit finite-difference method on the basis of the thermochemical $SiO_x$ production model [72].

### *2.3. Fiber Fuse Calculation of DCFs*

We assume that the DCF is in an atmosphere of $T = T_a$ and $r_1$ of the DCF is 200 μm (see Table 1). We also assume that part of the core layer is heated and has a length of $\Delta L$ (= 40 μm) and a temperature of $T^0_c$ (> $T_a$), as shown in Figure 3.

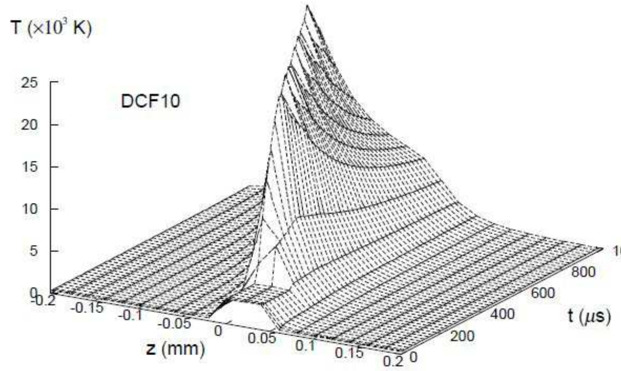


***Figure 4.*** *Core center temperature distribution in the longitudinal direction of DCF10 up to 1,000 μs after the incidence of laser light with $P_0$ = 2 W and $\lambda_0$ = 1.080 μm.*

In the calculation, we set the time interval δ$t$ to 10 ns, the step size along the $r$ axis δ$r$ to $r_1$/20, and the step size along the $z$ axis δ$z$ to 20 μm and assumed that $T^0_c$ = 2,923 K and $T_a$ = 298 K.

To investigate the formation process of the fiber fuse in the DCF10, we calculated the change in the temperature at the core center position with time after the incidence of laser power of 2 W at $\lambda_0$ = 1.080 μm. The calculated results are shown in Figure 4.

As shown in this figure, the core center temperature at the end of the hot zone ($z$ = 0 mm) increases to a large value of > $1\times10^4$ K in the 180 μs after the 2 W laser light incidence. Although a thermal wave with a peak temperature of higher than $2\times10^4$ K is generated at the end of the hot zone, it was found that this thermal wave does not propagate in the negative $z$ direction with the passage of time until $t$ = 360 μs, and thereafter propagation behavior was observed (see Figure 4). Such a stationary thermal wave was reported by Kashyap [73].

We estimated the changes in the temperature $T$ (0, $z$) at the core center ($r$ = 0 μm) in the DCF10 and DCF15 at $t$ = 1 ms after the incidence of laser light with $\lambda_0$ = 1.080 μm and initial power $P_0$ = 0-3 W and 0-6 W.

The calculated changes in the temperature at the core center position are shown in Figures 5 and 6. When the power of the light entering the DCF10 increases from 1.5 W to 1.6 W, the peak temperature rises from 2,923 to 21,000 K, and thereafter, propagation behavior was observed in the negative $z$ direction with increasing $P_0$, as shown in Figure 5.

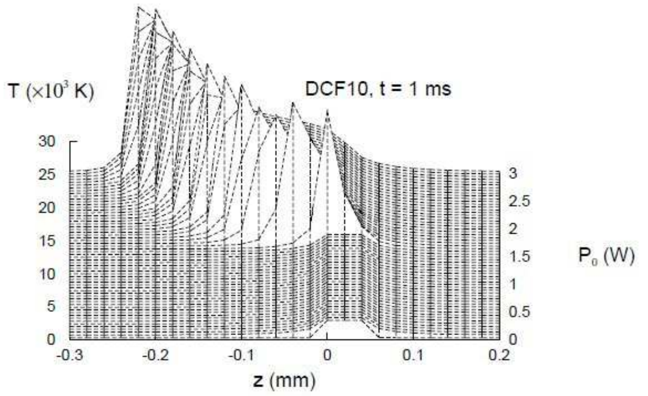


***Figure 5.*** *Core center temperature distribution in the longitudinal direction of the DCF10 after 1 ms with $P_0$ = 0-3 W and $\lambda_0$ = 1.080 μm.*

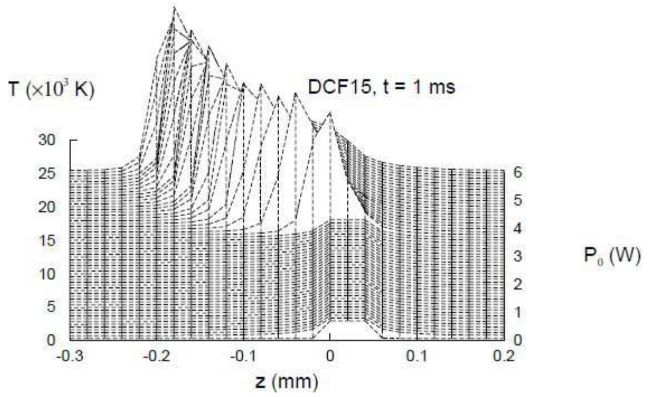


***Figure 6.*** *Core center temperature distribution in the longitudinal direction of the DCF15 after 1 ms with $P_0$ = 0-6 W and $\lambda_0$ = 1.080 μm.*

The characteristic $P_0$ value of 1.6 W is the threshold power $P_{th}$ of the DCF10. This value is close to the experimental $P_{th}$ value (about 2 W [68]) for the DCF with *a*~5.25 μm. The $P_{th}$ of the DCF15 is determined as 3.7 W in the same manner as the DCF10, as shown in Figure 6. This value is two times larger than that of the DCF10 because the $A_{eff}$ value (1,097 μm$^2$) of the DCF15 is larger than that (477 μm$^2$) of the DCF10 (see Table 1).

Next, we estimated the temperature field of the core center of the DCF10 along the *z* direction at *t* = 0.2 ms and 0.5 ms after the incidence of laser light with $P_0$ = 1.3 kW and $\lambda_0$ = 1.080 μm. The calculated results are shown in Figures 7 and 8. As shown in Figure 7, the core center temperature near the end of the hot zone (*z* = -1.80 mm) changes abruptly to a high value of about $2.8\times10^5$ K after 0.2 ms. This rapid rise in the temperature initiates the fiber fuse propagation, as shown in 8. After 0.5 ms, the high-temperature front in the core layer reaches a *z* value of -4.52 mm. The average propagation velocity $V_f$ is estimated to be 9.07 m/s using these data. This $V_f$ of the DCF10 is close to the value of 8.75 m/s measured by Sun *et al.* [69].

As shown in Figures 7 and 8, a sharp temperature peak located near the light source and a relatively high temperature plateau of about $2\times10^4$ K extending over 2-4 mm behind the sharp peak can be clearly seen. These regions located in the core are hotter than the surrounding cladding regions.

We examined the $P_0$ dependence of the $V_f$ values for the DCF10 and DCF15 at $\lambda_0$ = 1.080 μm. The results are shown in Figure 9. In this figure, the open circles and open triangle are the data reported by Sun *et al.* [69] and the closed circle is the datum reported by Xiao *et al.* [70]. As shown in Figure 9, the calculated $V_f$ values are close to the experimental values.

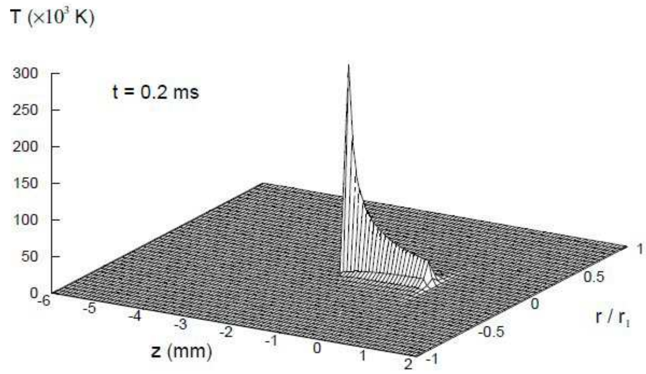


***Figure 7.*** *Temperature field in DCF10 after 0.2 ms when $P_0$ = 1.3 kW at $\lambda_0$ = 1.080 μm.*

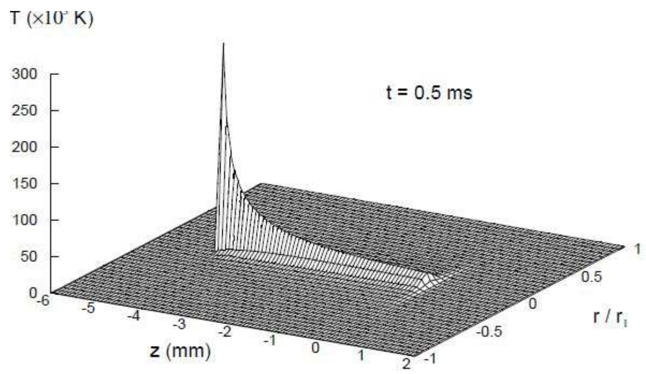


***Figure 8.*** *Temperature field in DCF10 after 0.5 ms when $P_0$ = 1.3 kW at $\lambda_0$ = 1.080 μm.*

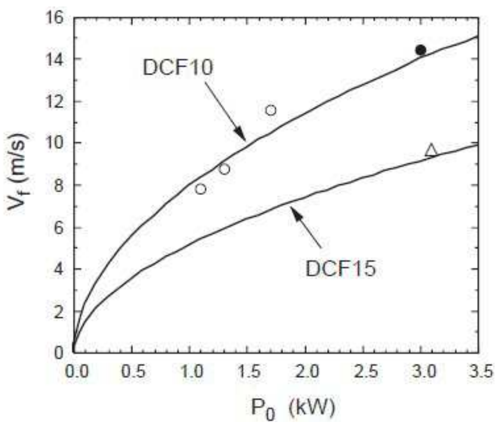


***Figure 9.*** *Power dependence of the fiber fuse propagation velocities of the DCF10 and DCF15 at $\lambda_0$ = 1.080 μm. The open circles and open triangle indicate the data reported by Sun et al. [69] and the closed circle indicates the datum reported by Xiao et al. [70].*

### *2.4. Power Dependence of Cavity Interval*

Sun *et al.* reported the interval Λ and length *l* values of the cavities at $P_0$ = 1.1, 1.3, 1.7 and 3.1 kW [69]. The experimental Λ and $l$ values are listed in Table 2 together with the reported $V_f$ values.

The relationship between the propagation velocity $V_f$ and the interval Λ is given by

$$\Lambda = \phi V_f \quad (6)$$

where ϕ is the period of the fiber fuse.

We estimated the ϕ values using Eq. (6) and the data listed in Table 2 at $P_0$ = 1.1, 1.3, 1.7 and 3.1 kW. The calculated results are shown in Figure 10.

***Table 2.*** *Cavity intervals and propagation velocities of fiber fuse [69].*

| $P_0$ (kW) | $V_f$ (m/s) | Λ (μm) | $l$ (μm) |
|---|---|---|---|
| 1.1 | 7.82 | 64.4 | 26.1 |
| 1.3 | 8.75 | 167.4 | 57.6 |
| 1.7 | 11.58 | 233.1 | 73.8 |
| 3.1 | 9.68 | 188.1 | 96.2 |

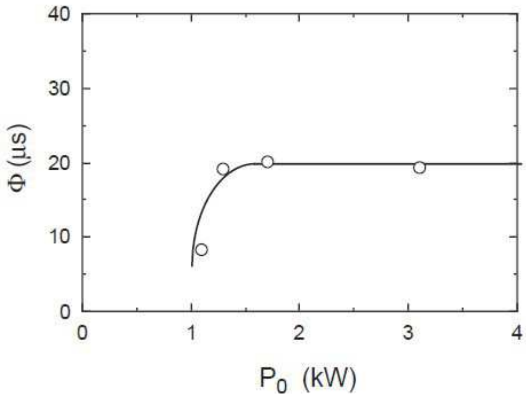


***Figure 10.*** *Relationship between the period ϕ and the input power $P_0$. The open circles are the values calculated using the data reported by Sun et al. [71].*

As shown in Figure 10, ϕ increases with increasing $P_0$ and gradually approaches to a constant value of about 20 μs at $P_0$ > 1.3 kW. This value (20 μs) is close to the ϕ (19 μs) observed at $P_0$ > 6 W in the conventional SMFs (see Figure on page 283 in [74]).

The period ϕ corresponds to the time required for the formation of one cavity during fiber fuse propagation [75] and ϕ~20 μs is the one under the thermodynamically stable condition of fiber fuse propagation.

Therefore, it can be seen from Figure 10 that fiber fuse propagation in the DCF10 and DCF15 is stabilized at $P_0$ > 1.3 kW.

It is well known that the fiber fuse phenomenon occurs when a light-absorbing substance (such as dust) is applied to the end face of a fiber and/or when a small region of a fiber core is melted by a fusion splicer using arc discharge [72].

Furthermore, failures at bends are caused by the light that leaks from the core when the fiber is accidentally tightly bent under high power [76]. In order to suppress HOMs, a bend radius of the DCF is controlled to increase the bend loss of $LP_{11}$ mode while keeping a low bend loss of $LP_{00}$ mode [27]. Further investigation focused on the relationship between the fiber fuse effect and the bending loss in DCFs is needed to improve the reliability of DCFs for high-power fiber lasers.

# 3. Conclusion

For the large-mode-area double-clad fibers (DCFs), fiber fuse propagation was investigated theoretically by the explicit finite-difference method using the thermochemical $SiO_x$ production model. The threshold power for the DCF with the core radius of 10 μm was 1.6 W at 1.080 μm and it was close to the experimental value. The power dependence of the velocity of fiber fuse propagation was calculated for the DCFs with the core radius of 10 and 15 μm. The calculated velocities were in fair agreement with the experimental values observed at 1.080 μm.

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