PHOTONICS Research

High absorption large-mode area step-index fiber for tandem-pumped high-brightness high-power lasers

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A short absorption length ytterbium (Yb)-doped large-mode area (LMA) fiber is presented as a step forward to mitigate the stern problem of nonlinear scatterings in a tandem pumping scheme adopted for high-power fiber laser. The short absorption length was realized by incorporating high Yb concentration in the fiber core. Furthermore, by replacing the inherent silica cladding with a Ge-doped cladding, we were able to obtain low core numerical aperture (NA) and negate the detrimental effect of index-raising by high Yb concentrations. This overcomes the long-standing limitation in step-index Yb-doped fibers (YDFs) where high cladding absorption inevitably results in high NA, thus hampering single-mode operation. We report an LMA (~575 μm^2) YDF with NA of 0.04 and absorption of 27 dB/m at 976 nm—both traits promote power scaling of single-mode tandem pumped fiber lasers. To our knowledge, this is the highest cladding absorption attained in a low-NA step-index fiber to date. An all-fiber tandem-pumped amplifier was built using only ~14 m of the YDF. The amplifier delivered a near-Gaussian beam ($M^2 \sim 1.27$) at 836 W output power (pump power limited) with a high slope efficiency of ~83%. Thanks to the short length and the tandem pumping, no indication of limiting factors such as stimulated Raman scattering, photodarkening, and transverse mode instability was observed.

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1. INTRODUCTION

Tandem pumping is an attractive solution in power scaling of fiber laser as it greatly eases out heat-related limits such as transverse mode instability (TMI) and helps single mode operation [1,2]. Adoption of the tandem pumping requires a long length of a gain fiber because of lower absorption cross section of rare-earth ions [such as ytterbium (Yb)] at a tandem pumping wavelength. Consequently, nonlinear scattering such as stimulated Raman scattering (SRS) becomes an ultimate limit of the tandem pumping scheme in a large-mode area (LMA) step-index fiber when the core size cannot be scaled further in the interest of beam quality control [1]. On the other hand, good beam quality in fiber lasers is achieved through preferential fundamental mode (FM) amplification in a gain fiber. The most common gain fiber is the step-index fiber, which is known for its robustness, reliability, and cost effectiveness in mass production. For a step-index fiber, the number of guided modes is determined by the V number, $V = \pi D_{\text{core}}\text{NA}/\lambda$, where D_{core} is the core diameter, NA is the numerical aperture, and λ is the wavelength; and the fiber supports only one mode if $V < 2.405$ [3]. Most single-mode high-power lasers, however, employ LMA gain fibers, e.g., with $D_{\text{core}} \approx 30$ μm and $\text{NA} \approx 0.06$ for better power handling [4,5]; despite $V \approx 5.3$ at $\lambda = 1.06$ μm for these fibers, effective FM operation was demonstrated through bend-induced losses of the higher-order modes (HOMs) [6–8].

To power-scale single-mode lasers further to several kilowatts, the threshold for nonlinear effects has to be raised, and this is commonly attained by increasing the core diameter to reduce the signal intensity; however, V increases as a result and it becomes more difficult to filter the HOMs. In addition, the most practical method to suppress the TMI is perhaps utilizing a modal discrimination bending effect [9], which is more profound in a low V number. Thus, the core NA must be reduced to maintain a low V number for beam quality control and power scaling. A straightforward method to reduce the core

NA is through reducing the dopant concentration of Yb ions. The Yb ions have a high molar refractivity (7.8×10^{-3} per mol% in Yb_2O_3 [10]) compared to other common dopants in a laser fiber, and thus contribute the most to the core refractive index. Through this approach, Yb-doped fibers (YDFs) with NA as low as 0.04 have recently been demonstrated in Refs. [10,11]. However, they come at the cost of a poorer pump absorption rate (0.2 dB/m [9] and 0.5 dB/m [12] at 976 nm), which clearly illustrates the problem of a step-index design. Low NA (<0.06) and high absorption (>1000 dB/m core absorption) cannot be simultaneously satisfied [13–15]. The difficult problem has hampered the adoption of tandem-pump amplifiers because they have to use a very long YDF that reduces thresholds of nonlinear effects [16,17]. Special fiber designs including microstructured fibers (e.g., in Refs. [18,19]) and other approaches [20–26] could be useful to get around the step-index fiber problem, but with increased complexity of fiber handling (such as cleaving and splicing) and fabrication.

Here, we report a highly efficient tandem pumped fiber amplifier using a very short absorption length YDF that features a low-index fiber of core NA 0.04 with simultaneous high pump absorption rate of 27 dB/m at 976 nm. The low NA highly doped Yb core is achieved by replacing the silica cladding with a germanium (Ge)-doped cladding and subsequently reducing the NA of the core. In particular, our fiber consists of the Ge-doped cladding and an Yb-doped alumino-phosphosilicate core that was tested to exhibit excellent photodarkening (PD) suppression [27]. Our previous report presented the feasibility of this Ge cladding approach via a standard modified chemical vapor deposition (MCVD) process and solution doping method [28]. In this work, we demonstrate high-power monolithic fiber amplifier using an LMA Ge cladding Yb fiber with a very low core NA of 0.04 and a record high cladding absorption of 27 dB/m for a step-index LMA fiber. The fiber has a core with average step-index of 6×10^{-4} with respect to the Ge cladding. The index fluctuations are kept within $\pm 2 \times 10^{-4}$ for the Ge cladding and $\pm 1 \times 10^{-4}$ for the Yb core—close to the 1×10^{-4} tolerance commonly reported for the MCVD process [28]. The achieved low NA promotes single-mode propagation and a large FM area, while the high pump absorption rate shortens the gain fiber length; these traits enable power scaling of single-mode lasers via tandem pumping. The fiber was tandem-pumped at 1 kW 1018 nm pump power to generate 1064 nm signal power of 836 W (pump power limited) with an excellent efficiency of 82.5%. Thanks to the high absorption low NA design, the amplifier was optimized at ~14 m of the YDF that delivered a near-Gaussian beam of $M^2 = 1.27$ at maximum output power. Hence, our results show greater potential for enabling multi-kW lasers [29].

2. FIBER DESIGN AND FABRICATION

To lase efficiently with near-single-mode output in a step-index LMA fiber, a simple fiber bending technique was found effective to impose differential bending loss of >10 dB/m in HOMs and <0.03 dB/m in an FM, which was determined via rate equation simulations [4,30]. As our fiber, despite the Ge cladding, has a step-index profile, these criteria should be applicable to safeguard the desired FM operation, as represented in Fig. 1. A commercial eigenmode solver and propagator [31] was employed to study the modal bending loss in a 30 μm core step-index fiber. The fiber NA was varied to probe the bend losses across a range of coil radii. The study took into account fabrication tolerance of 2×10^{-4} fluctuations in both the core and cladding indices, obtained from observation of our fabrication process; for example, see Figs. 2(a) and 2(b).

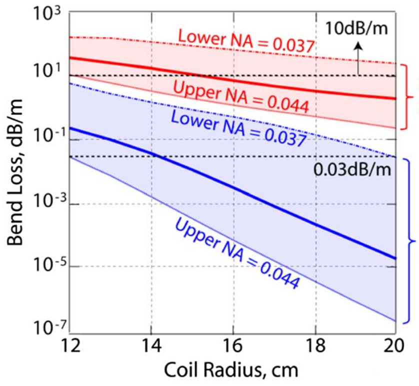

Fig. 1. Simulated bend losses of LP_{01} FM (blue) and LP_{11} HOM (red) for a 30 μm step-index fiber modeled with 2×10^{-4} index fluctuations (as fabrication tolerance) in the core and cladding. The solid lines are the predicted performance based on the measured RIP of the fiber reported in this work [see Fig. 2(a)].

The lower and upper bounds on the NA required to meet the good beam quality criteria were found to be 0.037 and 0.044, respectively, as shown in Fig. 1. This corresponds to a core index step of 4.8×10^{-4} to 6.5×10^{-4} with respect to the cladding, highlighting the tight fabrication tolerances required on the index fluctuations. The allowable NA range can be increased by either reducing the refractive index fluctuations (or fabrication tolerance) further to less than 2×10^{-4}, or reducing the core size (but at the expense of the mode field area necessary for power scaling in lasers). Based on the fiber

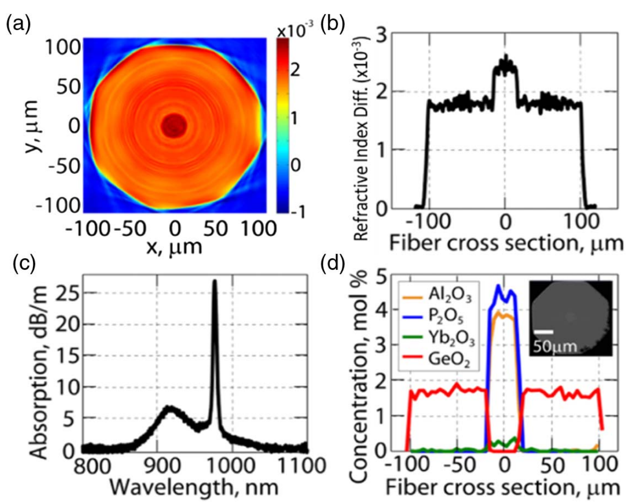

Fig. 2. Characterization results of the 30/200 low NA double-clad YDF that consists of a Ge-doped cladding and Yb/Al/P-doped cores. (a) 2D RIP, (b) 1D RIP, (c) cladding absorption, and (d) EDX dopant concentration profiles (SEM image of fiber cross section in inset).

refractive index profile (RIP) shown in Fig. 2(a), the fiber is predicted to exhibit bending loss performance following the red and blue solid lines (Fig. 1) for HOM loss and FM loss, respectively. Thus, the results clearly indicate that our fiber presented in Fig. 2 falls within the required NA range under the fabrication tolerances. And its optimal coiling radius is ∼15 cm for a robust single-mode operation. We note that bending of a low core NA fiber was demonstrated in many prior studies, e.g., in Ref. [12].

The low NA YDF in this work consists of a Ge-doped cladding to raise the cladding's refractive index by replacing a conventional silica cladding. The intent is to negate the index-raising Yb ions in the core to maintain a low NA. Using this approach, the trade-off between NA and Yb absorption is overcome to enable simultaneous low NA and high absorption. However, the required tolerances on the index fluctuations become tighter due to the smaller core index step ($\sim 6 \times 10^{-4}$) in a fiber, making fabrication challenging. Here, the MCVD and fiber drawing processes are optimized to achieve a reproducible recipe that demonstrates the highest cladding absorption in an Yb-doped low-NA LMA fiber to date, setting the stage for tandem-pumped higher-power single-mode lasers with a simple step-index design.

The fabrication process involves first depositing the Ge-doped cladding, followed by solution doping of the Yb-doped alumino-phosphosilicate core. During the deposition of Ge-doped cladding in MCVD, the $SiCl_4$ and $GeCl_4$ flow ratio is optimized to yield the required refractive index for the targeted core NA of 0.04, and pressurizing is employed to deposit multiple layers in order to build sufficient thickness of the cladding. Deposition of a phosphorus-doped (P) silica soot layer is then carried out and presintered to achieve the targeted soot porosity for solution doping, where Yb and aluminum (Al) are doped into the P soot via an alcohol-based solution to form the core. The preform subsequently undergoes oxidation and collapse steps before being sealed. P overdoping is carried out to completely remove the index dip in the core.

The round preform is subsequently shaped into an octagon using an ultrasonic milling machine to obtain the required cladding-to-core size ratio while ensuring low offset in core concentricity. The octagonal shaping is required to promote mode mixing of the pump light to enhance cladding absorption. A silica cladding inherited from a substrate tube was removed during the shaping. Hence, the octagonal cladding consists purely of the deposited Ge-doped cladding. Finally, mechanical and fire polishing are carried out on the preform to produce an optically transparent surface finish before fiber draw. The draw condition is optimized to produce a YDF that is mechanically strong for handling and able to undergo standard fiber stripping, cleaving, and splicing processes just like a conventional silica cladding step-index fiber.

3. FIBER CHARACTERIZATION

The RIP of the fiber is measured with Interfiber Analysis IFA-100 fiber index profiler using index oil with a matching refractive index to a silica substrate tube. The two-dimensional (2D) refractive index representation of the YDF is given in Fig. 2(a). The core diameter is found to be 30 ± 0.3 μm (full width at half-maximum), with flat-to-flat cladding diameter of 200 ± 2 μm, and core concentricity offset of 1 μm. Figure 2(b) is a one-dimensional (1D) slice of the refractive index taken from flat-to-flat axis of the 2D data in Fig. 2(a). It should be noted that the baseline of zero refractive index accounts for the index matching oil. Subsequently, the Ge cladding is the outermost layer in the fiber and completes the simple step-index fiber with the Yb core. The average index of the raised Ge-doped cladding with respect to the index matching oil is 1.8×10^{-3}, and the average core index is 2.4×10^{-3}. This gives a core index step of around 6×10^{-4} with respect to the cladding, which corresponds to an NA of 0.04. Modal analysis is carried out on the 2D RIP in Fig. 2(a), and the modal area of the FM predicted from simulation is 575 μm^2 at 1065 nm under the assumption of fiber bending at a 15 cm radius. In contrast, conventional LMA step-index fibers suitable for single-mode lasers have mode areas of 362 μm^2 [4]. The significance of the 1.5 times increase in area is a corresponding increase in the laser power before nonlinearities, such as SRS, set in to limit power scaling. We also note that the raised cladding gives rise to a cladding NA of 0.47 with the conventional low-index coating polymer (having a nominal refractive index of 1.373).

From Fig. 2(c), the Yb absorption at 976 nm is found to be 27 dB/m, which corresponds to a core absorption of 1200 dB/m—this is higher than any reported low-NA YDFs (for instance Refs. [7,11,12,18,19,27]). Its cladding absorption at the tandem pumping wavelength of 1018 nm is measured as ∼1 dB/m, which is comparable to the absorption at the diode pumping wavelength of 915 nm in a commercial LMA fiber, for instance Ref. [32]. Thus, our YDF enables a very short tandem-pumped fiber laser with the benefits of low thermal load. In addition to the larger mode area, this short absorption length will push further the nonlinear limits in average power scaling. Figure 2(d) shows the dopants' distributions retrieved from an energy-dispersive X-ray (EDX) analyzer with the scanning electron microscopy (SEM) image of the fiber end face in the inset. The average GeO_2 concentration in the cladding is 1.7 mol% and the average P_2O_5, Al_2O_3, and Yb_2O_3 concentrations in the core are 4.4 mol%, 3.8 mol%, and 0.29 mol%, respectively. The high concentration of P_2O_5 plays two roles: it promotes formation of $AlPO_4$ in the presence of Al_2O_3 to suppress the refractive index of the core [15,33], and increases resistance to PD [27,34]. It is worth noting that commercial alumino-phosphosilicate YDFs employ undoped claddings, and so are limited to NA > 0.08 at similar level of Yb_2O_3 concentrations (based on molar refractivity of 7.8×10^{-3} per mol% [10]).

The resistance of the fiber against PD is important for its long-term stability and reliability. We conducted an accelerated PD test under core pumping as detailed in Ref. [28]. The fiber showed insignificant PD loss. We repeated the PD test in a cladding-pump configuration to confirm the PD performance. With a 15 cm sample under near 40% inversion by a 915 nm laser diode cladding pumping, the probe wavelength loss at 635 nm was nearly negligible. We attribute this good PD performance to the 15 times higher concentration of P_2O_5 (compared to Yb_2O_3), which is known to be effective in mitigating PD [35].

4. ALL-FIBER HIGH-POWER AMPLIFIER

To study the optical performance of the fabricated low NA YDF, we employed an all-fiber forward-pumped amplifier configuration, as shown in the top of Fig. 3(a). The pump power was generated with a set of fiber oscillators at 1018 nm (similar to Ref. [36]), coupled into the YDF under test via a signal-pump combiner from ITF Technologies. We were able to splice the in-house YDF to the beam combiner using a conventional splicing condition, thus confirming the comformity of our Ge cladding fiber with conventional fiber components. A commercial 8.5 W fiber laser at 1065 nm was used as the seed laser for the amplifier setup. Thanks to the exceptionally high absorption, only 13.8 m of the YDF was required to absorb the pump light. It is worth mentioning that this length is nearly 3 times shorter than other tandem-pumped YDFs [37,38], hence promising 3 times larger power scaling potential. The in-house YDF was placed within grooves on a water-cooled spool at a set temperature of 16°C, and coiled at a radius of 15 cm (based on the results in Fig. 1). The laser was terminated by a commercial end cap and collimator. The output was directed to the beam diagnostics setup shown in the bottom plot of Fig. 3(a). A photodiode was placed at the output to observe the temporal trace of the output signal; by measuring the standard deviation of this signal, the onset of TMI can be determined [39].

The amplifier was tested up to 1 kW of pump power to produce an output of 836 W at 1065 nm, achieving an optical-to-optical efficiency of 82.5% at maximum power and a slope efficiency of 83.0% [see the top plot of Fig. 3(b)]. From these results, the background loss of the YDF is calculated to be less than 25 dB/km from rate equations modeling; this is well within commercial fiber specifications. Despite the high doping levels of Yb_2O_3, the YDF attained a thermal slope of 0.017°C/W to only reach a maximum temperature of 42°C, which is close to commercial YDFs that have been tested in the same setup. The inset in Fig. 3(b) shows the output spectrum of the amplifier, with a center wavelength at 1064.7 nm and a 3 dB linewidth of 2.0 nm at maximum power. A 20 dB difference in spectral intensity between the pump at 1018 nm and the signal at 1065 nm suggests that the output power and efficiency measured in Fig. 3(a) are due entirely to the desired signal, and there is little contribution from the leftover pump power. Moreover, the amplified spontaneous emissions can be suppressed to at least 35 dB below the signal. It is also worth noting that no SRS onset appears.

The laser beam quality was measured with a Spiricon M^2 – 200 s beam propagation analyzer; the results are shown in the bottom plot of Fig. 3(b). Under amplification, the beam quality improved from $M^2 = 1.42$ with just the seed laser to $M^2 = 1.27$ at 665 W output, despite having mismatched mode field areas of the fibers at both the input and output splices. There was no observable M^2 degradation up to 836 W. This clearly validates the low NA step-index YDF's ability to effectively suppress all HOMs amplification through high bend losses, while preserving only the FM, even with a large modal area of 575 μm². This result reassures the reliability of the Ge cladding to form a step-index fiber. In addition, there was no measurable increase in the standard deviation of the signal fluctuating in the kHz range; this indicates that the fiber amplifier has yet to reach the TMI threshold, and the experimental setup is currently pump-limited.

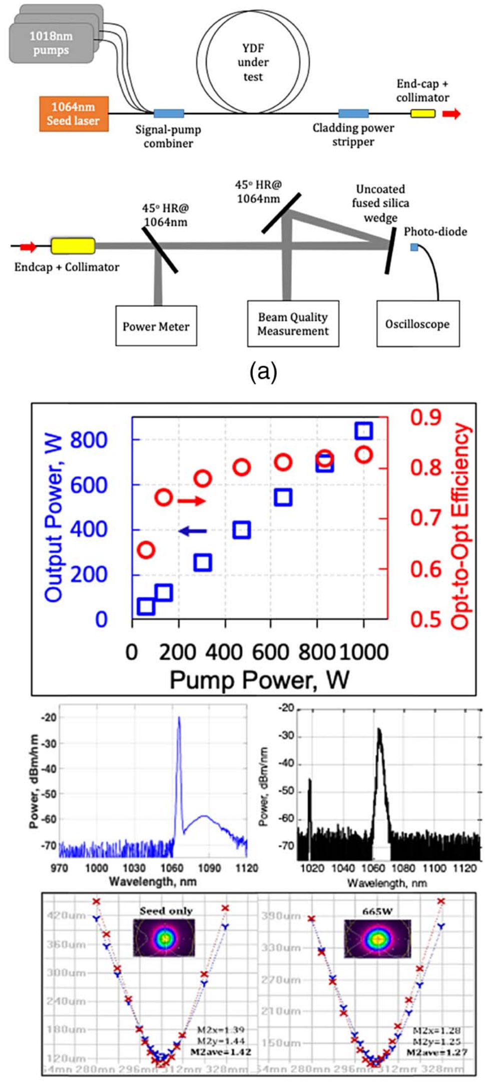

Fig. 3. (a) All-fiber tandem-pump laser setup (top) with its free-space beam diagnostics layout (bottom). The red solid arrow indicates direction of the laser output beam. (b) Optical performance of the fabricated low NA YDF. Top, the output power and efficiency of the amplified signal at 1065 nm, plotted with respect to the pump power at 1018 nm; middle, the spectra of the seed (left) and the amplified signal (right); bottom, M^2 of the laser output before (left) and after (right) amplification.

5. CONCLUSION

We fabricated a low NA 0.04 step-index YDF that possesses simultaneously high cladding absorption of 27 dB/m at 976 nm. This was enabled by an index-raised Ge-doped cladding to negate the index raising by the high Yb concentration, as well as low refractive index fluctuations of below 2×10^{-4} across the fiber. The FM field area calculated from the measured RIP was 575 μm². Furthermore, negligible PD-induced loss at 635 nm was detected over 1 h at near 40% inversion. To our knowledge, this is the highest cladding absorption attained in any low NA step-index YDF. The YDF was employed in a tandem-pump amplifier and tested up to 1 kW of pump power to produce an output of 836 W and an optical-to-optical efficiency of 82.5%, with no sign of rollover. Despite the lower absorption cross section at 1018 nm (~1/25 of 976 nm), the amplifier was constructed with a YDF length of only 13.8 m, thanks to the high absorption, and thus beneficial to nonlinearity suppression. Furthermore, because of the inherent low thermal load in a tandem pumping scheme, such a short length fiber does not raise a thermal issue. Hence, we demonstrated a power scaling route through tandem pumping for low thermal load and low nonlinear scattering. The beam quality improved under amplification to give M^2 of 1.27 enabled by the step-index design.

The laser experimental results validate the reported low NA YDF design and our fabrication processes, in addition to the YDF's ability to handle high power and withstand thermal load. Furthermore, our low NA YDF is demonstrated in an all-fiber monolithic laser setup, which further illustrates its robustness to cleaving and splicing. These results exhibit the potential of the Ge-doped cladding YDFs to outdo the conventional trade-off between beam quality, LMA, and high cladding absorption in order to enable further power scaling in single-mode fiber lasers. Our recent demonstration of ultrafast fiber lasers using the same fiber approach [40] suggests another meaningful application enabled by the presented fiber design.

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