An ultra-low NA step-index large mode area Yb-doped fiber with a germanium doped cladding for high power pulse amplification

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High concentration rare earth doped, large mode area (LMA) step-index fibers which feature a very high cladding absorption per unit length at the pump wavelength, high efficiency and excellent beam quality are ideal for high power pulsed fiber lasers/amplifiers where large effective mode areas and short device lengths are crucial in order to reduce detrimental nonlinear effects associated with high peak power operation. In this paper, we propose a new way to realize such fibers simply by employing a Germania (GeO_2)-doped cladding rather than a pure silica cladding to offset the high refractive index associated with using a high concentration of ytterbium (Yb) in the core. This approach allows us to separate the two inter-linked fiber design parameters of pump absorption and numerical aperture (NA). Using a conventional modified chemical deposition process combined with solution doping, a low NA (0.04), large mode area (475 μm^2) silica core fiber is fabricated with a cladding absorption value of >20 dB/m, which is the highest value among LMA step-index fibers with NA < 0.06 so far reported. The fabricated Yb-doped fiber was tested in a high power picosecond amplifier system and enabled the generation of 190 ps laser pulses with a 101 μJ pulse energy and 0.5 MW peak power at an average power of 150 W.

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Impressive advances have been made in the field of ultra-fast fiber lasers over the last decade and such lasers are progressively replacing conventional solid-state lasers as they offer a compact device and relatively low cost of ownership for industrial applications requiring high average power, high pulse energy output [1]. This progress has hinged on advances in large mode area (LMA) fibers that help mitigate peak power scaling limitations imposed by either nonlinear phase shifts (Kerr effect), and/or nonlinear scattering (Raman or Brillouin). It is well known that a LMA core design and short fiber length are critical to minimize the effects of fiber nonlinearities [2]. A large mode area is typically achieved in step-index fibers by lowering the core NA. However, the need for a low NA limits the amount of ytterbium that can be incorporated within the core (the higher the Yb concentration the higher the associated refractive index of the doped glass). Consequently, use of a low NA core, compromises the pump absorption and leads to increased device lengths [3-6]. Novel fibers were proposed to overcome the limits associated with a standard step-index design [7-12], including photonic crystal fibers (PCFs) [9-12] which have served as the leading fiber platform for peak power scaling of fiber lasers. However, realization of a rare-earth doped PCF demands precise index matching of the doped core to the air/glass microstructured cladding, which becomes increasingly challenging in the LMA regime. Furthermore, use of PCFs poses various practical difficulties in terms of fiber fabrication, fiber handling and integration into all-fiber laser systems. Very recently, an alternative approach, the use of tapered optical fibers, has been introduced and extensively investigated [13-18]. Here, a LMA step-index fiber is tapered over its length, with the tapered end used as the signal input end to ensure fundamental mode coupling and the amplified signal output is coupled from the other larger core end. In this way the fiber nonlinearity can be reduced along the fiber length with the core area increasing towards the fiber end where the peak powers are highest. In one approach, the tapering process was implemented during the fiber draw which produced a tapered fiber of several meters length [13-16]. However, this complicates the fiber draw process and the draw parameters need to be adjusted on the fly which compromises the draw quality and limits the achievable tapering ratio and fiber yield [17]. Alternatively, the fiber tapering process can be introduced using a flame brushing technique after the fiber draw. An adiabatically tapered amplifier of <1 m length was used to generate 2 MW peak power pulses [18], but this requires special adaptations and precautions to realize long fiber tapers (i.e.. stripping, cleaning, tapering and recoating of a very long fiber) and leads to unwanted effects such as dopant diffusion and index profile modifications [17, 18]. Recently, we have reported a very high absorption step-index Yb-doped LMA fiber made using the conventional modified chemical vapor deposition (MCVD) process combined with the solution doping technique [19]. A high Yb concentration (~0.4 mol % of Yb_2O_3) was achieved using an equi-molar phosphorus (P) and aluminum (Al) composition that greatly suppresses photodarkening and refractive index increase [20, 21]. To compensate for the high refractive index of the core that results from the high Yb concentration, a Ge doped cladding is employed instead of a pure silica cladding to reduce the core NA to an acceptable value for a LMA fiber. The fiber typically gives >20 dB/m cladding pump-absorption which is at least 1.5 times higher than the typical commercial LMA PCF used for ultrafast fiber lasers [22, 23]. Due to the high cladding absorption, fibers fabricated by this approach are a particularly attractive gain medium for high peak power ultrafast lasers.

In this paper, we report the fabrication of ultra-low NA, high absorption, Ge-clad fibers and we experimentally investigate the amplification of picosecond pulses in a master oscillator power amplifier (MOPA) system to demonstrate the benefits. A high absorption LMA fiber with 475 μm² mode area and 0.04 core NA was fabricated and a 0.8 m length of this was used for efficient amplification of 190 ps laser pulses to 101 μJ pulse energy with 0.5 MW peak power at an average output power of 150 W. The power scaling is currently limited by available pump power and negligible stimulated Raman scattering (SRS) was observed. Good beam quality with a mean M^2 value of ~1.1 power was observed (at an average power of 32 W). In addition, basic characteristics of the Ge-cladding fiber is discussed which confirm that it behaves very similarly to conventional silica cladding step-index fiber.

A series of LMA step-index Yb-doped fibers was fabricated according to the fabrication procedures presented in [19]. The fiber core is comprised of silica doped with Yb, Al and P, while the cladding is doped with Ge to raise the refractive index. The fiber preform fabrication consisted of three steps: (i) Ge-doped cladding deposition, (ii) high Yb doped P: Al core deposition, and (iii) preform milling to obtain an octagonal shape while completely removing the silica outer cladding. A low-index polymer coating was then applied during fiber drawing to provide a cladding NA of 0.45. The fibers have different V-numbers in the range of 3.6 – 5.2 as listed in Table 1. The core sizes are 28 – 33 μm, with a cladding-to-core area ratio (CCAR) of ~47. The refractive index profiles of Fiber #2 and Fiber #4 are presented in Fig. 1 and Fig. 2, respectively. It should be noted that index matching oil was used to provide the measurement baseline and the index contrast between the Ge-doped cladding and the baseline is ~0.0022±0.0002 in Fiber #2 and ~0.0023±0.0003 in Fiber #4. The corresponding GeO_2 content in the cladding is estimated to be ~12 mol%. , The core NA is very well controlled within the range of 0.04–0.05 using our fabrication approach. It is worth noting that the fiber core NA was further reduced from our previous report (NA~0.07) [19] and the fabricated fibers are as readily cleaved and spliced as conventional silica cladding fibers.

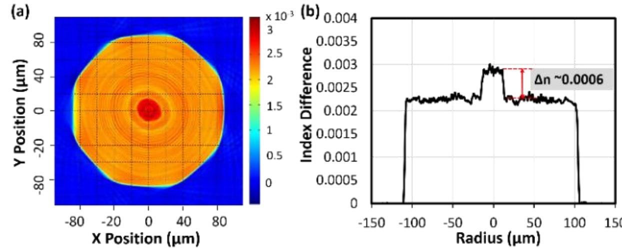

Fig. 1(a) 2D index profile and (b) 1D index profile of the fabricated 0.04 NA fiber with a core size of ~33 μm. (Fiber #2 in Table 1)

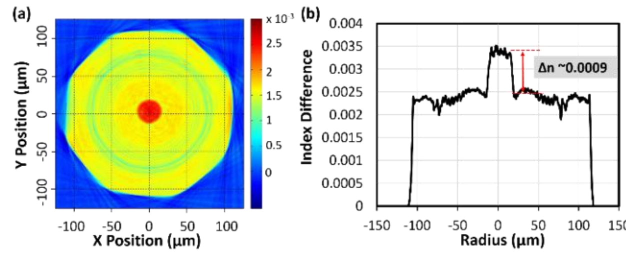

Fig. 2(a) 2D index profile and (b) 1D index profile of the fabricated 0.05 NA fiber with a core size of ~33 μm. (Fiber #4 in Table 1)

Table 1 Specifications of the fabricated LMA Yb fibers

Fiber Number	Δn	NA	Core Diameter (μm)	Cladding Diameter (μm)	V No
Fiber #1	0.0006	0.042	28	180	3.56
Fiber #2	0.0006	0.042	33	220	4.2
Fiber #3	0.0009	0.051	28	180	4.37
Fiber #4	0.0009	0.051	33	220	5.15

The cladding absorption of the fabricated fibers was measured to be ~22dB/m at 976nm using the cutback method. The high absorption is mainly due to the higher Yb_2O_3 concentrations (~0.3 – 0.35 mol %) and smaller CCAR, which enables a shorter fiber length for efficient high power ultrafast lasers.

As our fabricated fibers contain a Ge-doped cladding, we first studied simple CW laser operation to check whether the Ge cladding causes any anomalies in laser operation. A free running 4%-4% linear cavity was constructed as shown in Fig. 3. A wavelength stabilized laser diode at 976 nm was used as the pump source, which was coupled to the fiber under test (FUT) via lenses. The pump beam was separated from the signal beam by placing dichroic mirrors (DMs) at both signal output ends. One advantage of a step-index fiber, apart from its easy handling, is the ability to suppress higher-order core modes (HOMs) by coiling the fiber at an appropriate bend diameter [24]. The slope efficiency, output spectrum and beam quality were evaluated for all fabricated fibers as summarized in Table 2. Fig. 4(a) shows the total output power of the laser signal plotted against the launched pump power for a 0.77 m length of Fiber #3, with a bending diameter of ~10 cm. The slope efficiency was measured to be ~86% with a maximum output power of 32 W. The laser output spectrum at full power is shown in the inset of Fig. 4 (a), with a peak wavelength of ~1030 nm. The beam quality factor (M^2) of the laser beam was also evaluated at the maximum output signal power as presented in Fig. 4(b). A nearly diffraction-limited beam with a mean M^2 value of 1.24 was observed, confirming the effectiveness of the fiber coiling as similarly observed with a conventional silica cladding fiber. The other fibers (Fiber #1, #2 and #4) were also tested with the same procedure, and the results are shown in Fig. 5.

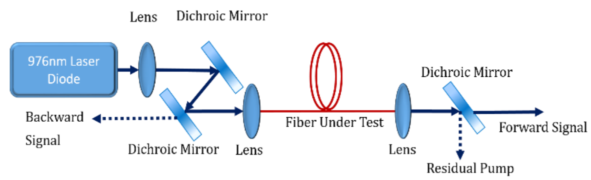

Fig. 3 Experimental fiber laser setup.

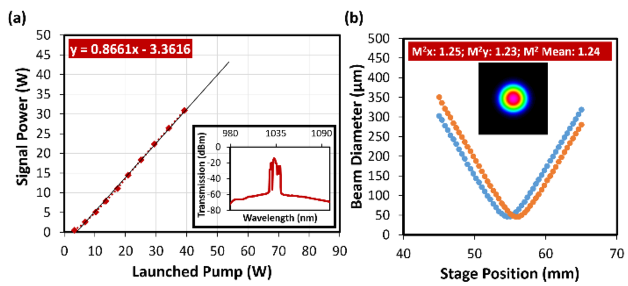

Fig. 4(a) Laser output power versus pump power in a 0.77m long 28µm-0.05 NA fiber (Fiber #3). The inset shows the laser spectrum at full power. (b) Measured beam quality factor at 32 W output power, with beam profile shown in the inset.

The V-number is the major parameter that determines the number of guided modes in a step-index fiber. Whilst a V-number of < 2.405 is ideally required for single mode operation, LMA fibers with a V-number below 5 can provide a good compromise between high power and good beam quality under bent fiber conditions [24, 25]. This is consistent with our results from the Ge-cladding fibers as presented in Fig. 5. By applying appropriate fiber bends, we were able to achieve a good beam quality in the fabricated fibers. Although not optimized, bending diameters in a range of ~10 cm for 0.05 NA fibers and ~40 cm for 0.04 NA fibers were applied in an attempt to attain a good compromise between efficiency and beam quality. Hence, it can be said that the Ge-cladding fibers work similarly to other silica cladding LMA fibers and the higher pump absorption enables very short fiber lengths (< 1 m) as required for high power ultrafast laser applications.

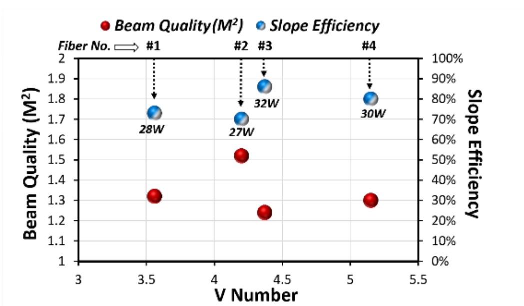

Fig. 5 Beam quality and laser slope efficiency of the Ge-cladding fibers against V number. The maximum output power for each fiber is shown below the respective markers in the figure as well.

In order to investigate ps pulse amplification in our fibers, an Yb-doped master-oscillator power amplifier (MOPA) system was employed and Fiber #2 (NA~ 0.04 and core diameter~ 33µm) was used in the final power amplifier stage. The schematic of the MOPA is shown in Fig. 6. A gain-switched laser diode was used as the seed source (operating at a wavelength of 1030 nm, emitting 190 ps pulses at a repetition rate of 1.476 MHz). The gain-switched signal was first amplified through a chain of pre-amplifiers at the end of which the average power was 0.75 W. The signal is subsequently launched in to a 0.77 m length of fiber (Fiber #2) through lenses (as shown in Fig. 6). An optical isolator is inserted in the coupling block to stop any signal light from propagating back into the pre-amplifier chain. Light from a 976 nm pump module is coupled to the other end of the fiber via a lens and dichroic mirror assembly. Fig. 7 (a) shows the amplified signal power plotted against absorbed pump power. A linear increase in the signal power is obtained with a slope efficiency of 72%, up to the maximum average power of 150 W. This is currently limited only by the available pump power. The amplified pulses have a pulse energy of ~101 µJ, corresponding to a peak power of 0.5 MW. Fig. 7(a) also shows the amplifier gain plotted against pump power, showing a saturated gain of ~23 dB at maximum power. Fig. 7(b) shows the spectrum of the output signal at full power (red curve). No evidence of SRS is observed and spectral broadening is minimal (a 3 dB bandwidth of 0.31 nm was obtained at full power). Furthermore, the performance of our in-house fiber is compared to that of a commercial 25/250 LMA fiber (Liekki), one of the largest absorption fibers (~10dB/m cladding absorption at 976 nm) among commercially available LMA step-index fibers [6, 26]. The output power increased linearly with nearly equivalent slope efficiency to the in-house fiber as shown in Fig. 7(a), but this time requiring a fiber length of 2.2 m. However, the power scaling in this instances was limited to 29 W because of the onset of SRS as indicated in the black curve in Fig. 7(b). The corresponding pulse energy was only 21 µJ and the spectral broadening was appreciable (3 dB bandwidth of 0.69 nm at just 20% of the pulse energy generated in the in-house fiber). In addition, our in-house fiber supports a close to diffraction limited beam with a beam quality factor (M^2) of ~1.06 measured at 45 W, as presented in Fig. 7(c). Table 2 compares the laser performance of the in-house and the commercial fiber. From this comparison, we believe that our proposed simple step-index LMA fiber with a raised Ge-cladding represents a promising way towards compact MW peak power fiber laser systems. Further improvements can be expected by further optimizing the fiber fabrication and mode stripping.

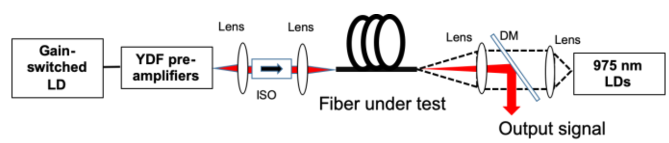

Fig. 6 A ps MOPA setup to test the high absorption fiber. The dashed lines indicate a pump beam path. LD: laser diode, YDF: Yb-doped fiber, ISO: isolator, and DM: dichroic mirror.

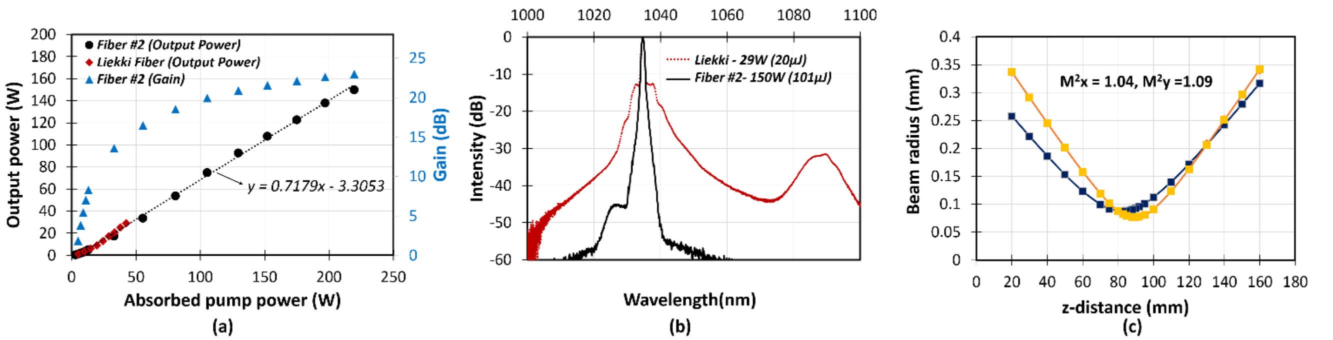

Fig. 7 (a) Output power (and Gain) vs pump power, (b) Output signal spectra at full power from an in-house (red curve) and a commercial fiber (black curve) and (c) beam quality of signal beam from an in-house fiber

Table 2 Performance comparison between the in-house and the commercial fiber in ultrafast laser amplification

Fiber	Length (m)	Output Power (W)	Repetition rate (MHz)	Energy(μJ)	Pulse Duration (ps)	Peak Power (kW)	Bandwidth(3dB)	Fraction of Energy within 3dB
Commercial Liekki fiber	2.2	29	1.367	21	110	190	0.69	56%
Fiber #2	0.8	150	1.475	101	190	530	0.31	46%

In summary, we have successfully fabricated a LMA step-index Yb-doped fiber with an ultra-low NA and a raised Ge-cladding. The raised Ge-cladding that replaces the conventional silica cladding effectively reduces the core NA and hence enables single-mode operation with a LMA core. The fiber offers the highest cladding absorption of > 20 dB/m obtained for a simple step-index LMA fiber, enabling effective reduction of fiber nonlinearities. The high fiber absorption does not compromise the output beam quality and the conventional mode selective bending loss approach for higher-order mode suppression is still found to be applicable in our Ge-cladding fibers. We were able to amplify 190 ps pulses to 101μJ pulse energy with 0.5 MW peak powers without any indication of SRS. A high average power of 150 W was extracted using just a 0.77 m length of fiber and an excellent beam quality with a mean M^2 of 1.06 was obtained at 45 W output power. These experimental results strongly suggest that this simple step-index LMA fiber approach could be a practical fabrication strategy to develop > MW peak power ultrafast fiber laser systems.

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