Fiber amplifier utilizing an Yb-doped large-mode-area fiber with confined doping and tailored refractive index profile

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ABSTRACT

Power scaling of Yb-doped large-mode-area fibers drives the scaling of the mode area in order to suppress nonlinearities. Two Yb-doped large-mode-area fibers were manufactured using the Direct Nanoparticle Deposition process: one with a step refractive index profile and active ion confinement, and another with a tailored refractive index and active ion confinement. The index tailoring and doping profiles were designed based on literature to enhance the beam quality of the fibers. Both fibers exhibited a mode field diameter comparable to a 40µm step index fiber with 0.07 NA. The fibers were characterized for their geometries, index profiles, and material composition profiles. Additional testing for beam quality and nonlinearities in pulsed operation was conducted using a power amplifier setup. The beam quality enhancement capability of the tested fibers was inconclusive due to incomparable launching conditions of the signal to the fibers.

Keywords: fiber amplifier, ytterbium, large-mode-area, confined doping, tailored refractive index profile

1. INTRODUCTION

Ytterbium doped fiber amplifiers are useful in a wide range of applications that require high average or peak powers, good beam quality, and low cost [1,2]. Most methods to achieve good beam quality from fiber amplifiers with double-clad large-mode-area (LMA) fibers have been based on inducing losses for the higher-order modes by coiling the fiber [3] or using a non step-index refractive index profile (see references in [4]). Novel fiber structures which reduce coupling between transverse modes have also been designed, for example by using an elevated index in the core [5]. Recently, confining the active ion doping area has been suggested as a method to favor the fundamental mode through preferential gain [4].

Using the Direct Nanoparticle Deposition (DND) technology, large-core fibers with radially and independently varying active ion concentration and refractive index profiles can be realized [6]. We report on the design and manufacture of double-clad LMA fibers in which the core has a central Yb-doped area with a flat refractive index, surrounded by a passive area that can have either a step- or radially decreasing refractive index profile as illustrated in Figure 1. Due to the confined doping, these designs are expected to offer preferential gain for the fundamental mode. Additionally, the tailored refractive index is expected to lower the mode coupling (through increased separation between propagation constants of the modes) and increase the higher-order mode losses.

In addition to the active fiber properties, seed launching conditions also have a major effect on the output beam quality. Through careful control of the input excitation conditions, single-moded operation can be achieved with multimoded fibers even without preferential gain for the fundamental mode [7]. In this work, fiber tapers are used as mode field adapters, which can convert the mode field between dissimilar core diameters and provide a stable launching condition for fundamental mode excitation in the fiber under test. The fiber tapers were realized using a draw tower. This enabled manufacturing of double-clad fiber tapers with a very smooth core diameter transition due to the relative long length of the device.

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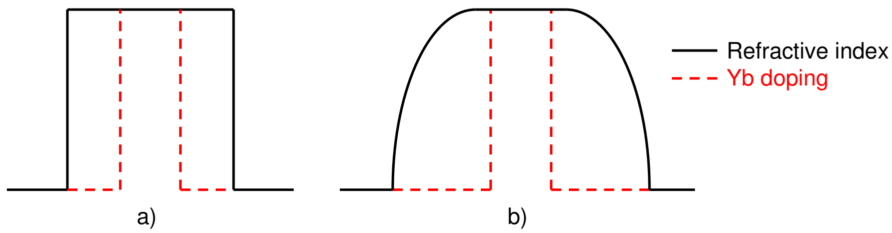


Figure 1. Refractive index and active ion profiles of the new fibers. a) step-index with confined doping b) tailored refractive index with confined doping

2. EXPERIMENT

Two ytterbium-doped large mode area fibers with a radial doping profile were manufactured with a cladding diameter of 400µm. A power amplifier setup was used to characterize their performance. The first fiber has a step-index core 44µm in diameter, out of which 28µm is doped with ytterbium. The second fiber core is 51µm in diameter with 32µm Yb-doped and its refractive-index profile is semi-parabolic. A standard step-index LMA fiber with 25µm core and 250µm cladding was used as a reference fiber. The fibers are referred to as Yb1200-28/44/400DC, Yb1200-32/51/400DC and Yb1200-25/250DC (Yb level – dopant diameter if applicable / core diameter / cladding diameter, DC = double-clad). A fiber taper was used for seed input coupling. The smaller end of the taper has a 25µm core and 250µm cladding diameter whereas at the output end, the core diameter is 40µm and the cladding diameter 400µm.

2.1 Manufacturing and characterization of the fibers

The fibers used in the experiments were manufactured using nLIGHT's proprietary DND (Direct Nanoparticle Deposition) fiber manufacturing process that is ideally suited for fibers with large cores and tailored refractive index and/or dopant profiles. The DND soot deposition process, shown in Figure 2, can use both gaseous and liquid raw material sources. The formation of doped silica glass soot takes place in the flame. The burner feeds the required dopants and co-dopants into the flame, enabling real-time radial control of the glass composition and the subsequent material properties, specifically the refractive index and the optically active dopant concentration. The soot is first deposited on a mandrel, then sintered, and finally collapsed. The preform can be manufactured by using a rod-in-tube sleeving process, making very large core to clad ratio fiber profiles feasible. A further benefit of the DND process is the homogeneity of the material, which is beneficial in reducing clustering related phenomena that can manifest as reduced efficiency (Erbium) or photodarkening (Ytterbium) [6, 8].

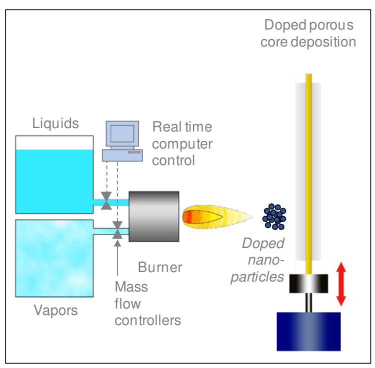


Figure 2. Schematic of Direct Nanoparticle Deposition process for doped silica soot deposition. Both liquid and vapor raw materials can be fed into the burner. The glass is formed in the flame, yielding doped silica nanoparticles that are subsequently deposited on a rotating and traversing mandrel.

Figure 3 shows the measured preform and fiber refractive index profiles of all the investigated fibers. The peaks at the doped/passive material interface of the Yb1200-28/44/400DC were attributed to stress-related index changes. Figure 4 shows the aluminum and ytterbium concentration profiles of the step-index Yb1200-28/44/400DC, measured using an Energy Dispersive Spectroscopy (EDS) coupled with a scanning electron microscope (SEM). To keep the refractive index constant in the core, the concentration of Al was decreased to compensate the incorporation of Yb in the center of the core.

For the Yb1200-32/51/400DC, further fiber process engineering resulted in a clear decrease in the refractive index ripple at the interface.

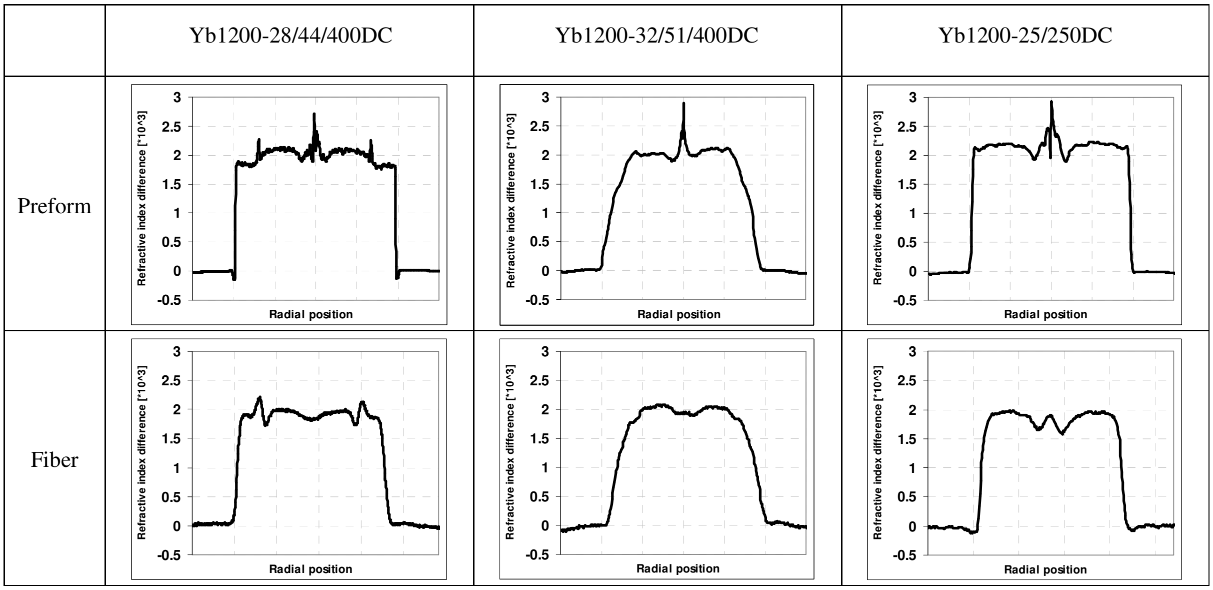


Figure 3. Preform and fiber refractive index profiles of the experimental fibers. The sharp index changes at the material interfaces are attributed to stress related index changes.

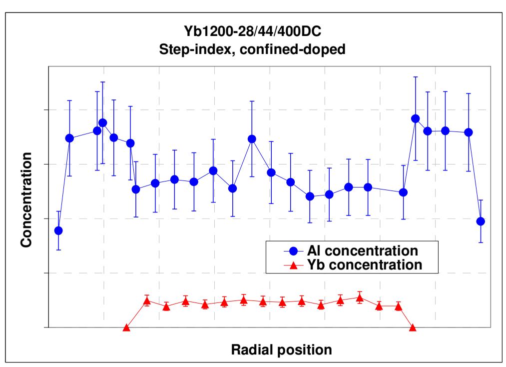


Figure 4. Radial SEM/EDS composition analysis of the core of the Yb1200-28/44/400DC preform. Error bars represent the 95% confidence interval as reported by the measurement equipment.

2.2 Manufacturing of the passive fiber tapers

Fiber based mode field adapters were used in the experiment in order to improve the fundamental mode excitation for the highly multimoded Yb doped fibers. Mode field adapter devices can be manufactured from fibers by tapering drawn fibers or by changing the core refractive index profile by applying enough heat to diffuse the dopants used in the core [9]. As the preservation of mode quality is expected to become increasingly more difficult with increasing core sizes due to decrease in mode propagation constant differences [5], the mode field adapter manufacturing method should be repeatable and accurate in order to prevent mode coupling. To meet these criteria, we chose to use draw tower made tapered devices to couple the signal into the fibers under study. The tapers were made from a passive preform during the fiber drawing by controlling the drawing process, and coated with a low index polymer in a manner typical for fiber drawing. The resulted tapers were approximately 2m in length and had the optical properties listed in Table 1. Figure 5 shows a cut-back measurement of the core diameter profile in a typical taper.

Table 1. Typical fiber taper parameters

Thin end core / cladding diameter	25µm / 250µm
Thick end core / cladding diameter	40µm / 400µm
Core NA	0.068
Cladding NA	0.46

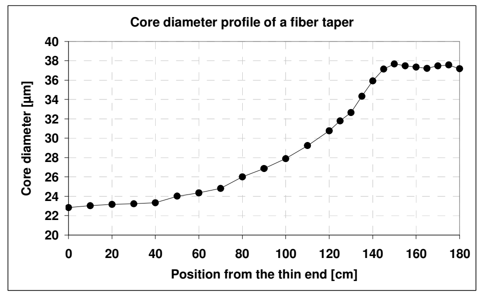


Figure 5. Measured core diameter profile of a typical fiber taper

2.3 MOPA setup for testing different fibers

In order to test the fibers, a master oscillator (MO) with an LMA fiber output was built and the different fibers were tested as power amplifiers (PA) as shown in Figure 6.

The MO consisted of a passively Q-switched microchip seed laser that was amplified using standard Yb1200-25/250DC fiber, and subsequently fiber coupled after isolation to a passive 25/250 output fiber. The passive input fiber was coiled on two axes and approximately 6cm diameter to strip out higher order modes, while the active fiber was loosely coiled on a 14-16cm diameter coil. The core and cladding NAs were 0.07 and 0.46, respectively. A cladding light dump was inserted to strip the excess forward propagating signal light and the excess backward propagating pump light. The pump was a 976nm fiber coupled Pearl pump module with a 200µm output fiber and 0.22 NA. An isolator was inserted to the output of the MO to prevent any feedback from the test fiber amplifier. The passive fiber after the isolator was coiled similarly as the input fiber on two axes and approximately 6cm diameter to remove higher order modes prior to further amplification.

The PA for each test fiber consisted of a taper fiber having 25/250 geometry in the thinner end and 40/400 geometry in the thicker end spliced to the tested Yb-doped DC fiber. Each tested DC fiber was mode field diameter matched to the output of the taper fiber in order to reduce the amount of higher order modes launched into the power amplifier. The tested DC fibers were loosely coiled on a 16cm diameter, and not actively cooled. Signal output and pump input coupling was done with two lenses. The signal output was reflected to the power meter or laser beam analyzer using a dichroic mirror.

The fibers were characterized for beam quality by performing a M^2 measurement with a Spiricon M^2-200 laser beam analyzer. Due to the high peak and average powers, two reflecting silica wedges and neutral density filters were placed between the signal output and the M^2-200 system. The nonlinearities were characterized by comparing the output signal spectral shapes at the same output power level. The output spectrum was measured from a reflection from the output power meter.

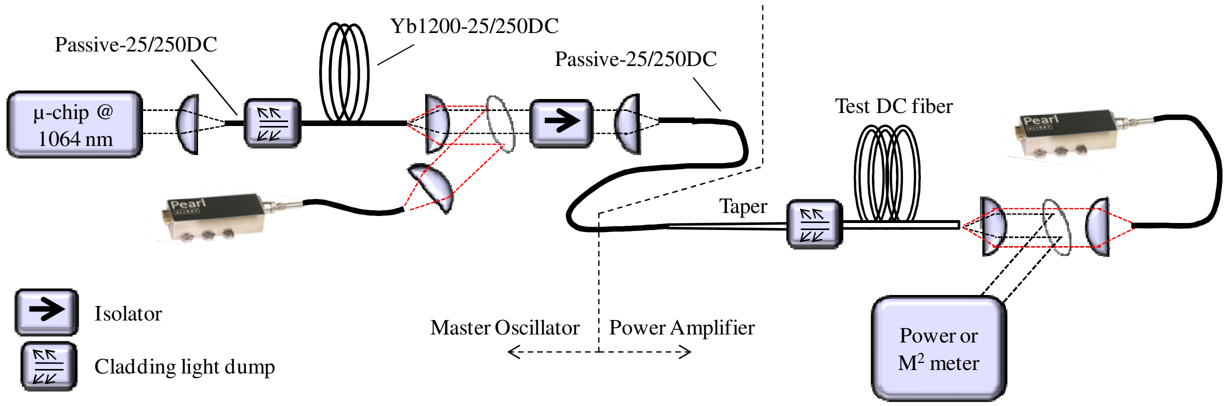


Figure 6. Amplifier setup used to test the fibers.

Table 2 summarizes the key parameters of the tested fibers. In addition to the three active fibers, a passive fiber with a 40µm step-index core was also used to study effect of the splice on the beam quality. The fundamental mode MFDs were simulated using the Liekki Application Designer 4.0.

Table 2. Information on the fibers used in the experiment.

Fiber type	**Core diameter [µm]**	**Yb-doped area diameter [µm]**	**Core refractive index profile**	**Core NA**	**Simulated LP01 MFD [µm]**	**Cladding diameter [µm]**	**Cladding NA**
Yb1200-28/44/400DC	44	28	Step	0.076	28.4	400	0.46
Yb1200-32/51/400DC	51	32	Tailored	-	27.0	400	0.46
Yb1200-25/250DC	25	25	Step	0.077	19.2	250	0.46
Passive-40/400DC	40	-	Step	0.068	27.9	400	0.46

3. RESULTS

3.1 Beam quality at the input of the power amplifier

Beam image and M^2 values with various launch conditions are shown in Figure 7. Initial seed quality after the coiling of the 25/250 fiber is very good (Figure 7a). However, when the taper was spliced on, the beam quality unexpectedly got clearly worse (Figure 7b). Adding a further 2m of passive 25/250 fiber onto the mode stripper did not seem to change the initial beam quality, but after adding the taper again a noticeable improvement was observed (Figure 7d). Most likely, there was some amount of power in the higher order modes after the short mode stripper, even though the M^2 value was good. The same behavior was observed when the passive-40/400DC fiber was spliced to the output end of the taper. An improvement from ~1.4 to ~1.2 in the M^2 value was observed with increased mode-stripper length (Figures 7c and 7e). The beam quality degradation between the output of the taper and the output of the 400µm passive fiber is due to the higher-order modes generated at the splice point. The large core diameters and low NAs of the fibers involved make this splice very sensitive. The possibility of the RIP mismatch is eliminated by the fact that the tapers and the 400µm passive fiber were drawn from the same preform.

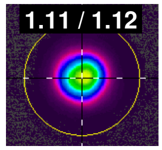
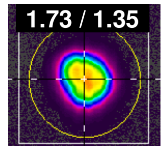
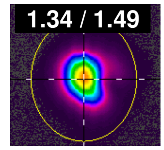
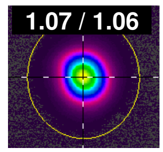
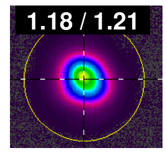
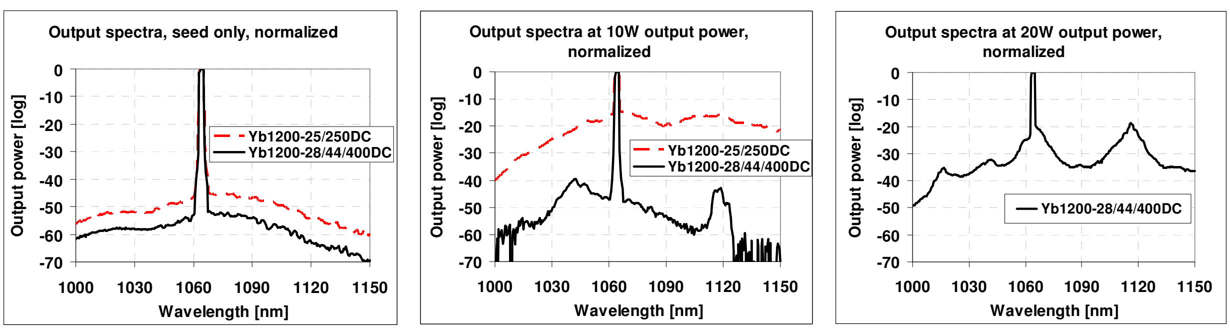
	Output of the mode stripper (passive 25/250, 6cm coil)	Output after a taper	Output after a taper and 40/400DC passive
Short mode stripper (L=2.2m)	 a)	 b)	 c)
Long mode stripper (L=4.2m)		 d)	 e)

Figure 7. Measured M^2 values (x-axis / y-axis) and beam images of the seed signal before the active fiber.

3.2 Nonlinearities in step index and confined doped fiber

The nonlinearities were characterized by comparing the output spectrum between the conventional Yb1200-25/250DC and the confined-doped Yb1200-28/44/400DC. The fiber amplifier always works at 50kHz with a FWHM pulse duration of 1.2ns. No nonlinearities are visible in the seed source spectrum even when the 0.5W seed signal is passed through the active fiber (Figure 8a). At 10W average output power, in the case of the conventional LMA fiber with a 25µm, and 0.077NA core, the nonlinearities are so strong that the output spectrum resembles a continuum between 1000nm and 1150nm (Figure 8b). In comparison, only a 43dB below the signal level Raman peak is visible in the fiber with a 44µm confined-doped core. At 20W average output power, even the larger-core fiber yields a continuum-like output spectrum (Figure 8c). The 25µm core fiber was not pushed to this high output power due to a risk of pump laser damage.



a) b) c)

Figure 8. Output spectra of Yb1200-25/250DC and Yb1200-28/44/400DC fibers. a) Seed only b) 10W output power c) 20W output power

3.3 Beam quality of step index and confined doped fiber

The beam quality of the step index and confined doped fiber was measured from the output of the power amplifier. Figure 9 shows the measured M^2 values of the Yb1200-28/44/400DC and the Yb1200-25/250DC fibers as a function of output power. While the 25µm core fiber maintains very good beam quality at all measured output powers, the 44µm confined-doped core fiber suffers from higher order mode content. This is attributed to mode coupling in the splice point, given the good beam quality results obtained from a passive fiber taper only.

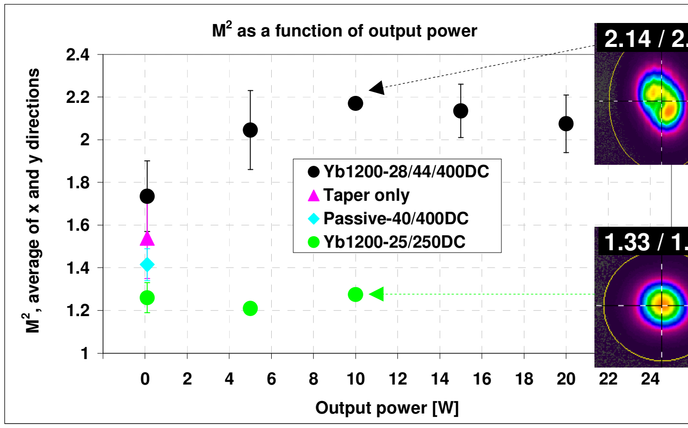


Figure 9. M^2 comparison of conventional Yb1200-25/250DC and confined-doped Yb1200-28/44/400DC. Dots present an average value of M^2, and the vertical lines indicate the difference in the x- and y-axis direction. Insets show output beam images of both fibers at 10W output power.

3.4 Beam quality of confined doped and index tailored fiber

Figure 10 shows the output power dependent M^2 value for the confined-doped and refractive-index tailored Yb1200-32/51/400DC. Maximum output power was 35W due to a higher-power pump module used for this fiber. While the M^2 value is close to two, the output signal beam exhibited a more symmetrical shape than in the case of step index confined core case. This is illustrated in the inset in Figure 10, and can be seen as small error bars in the same figure. Again, unoptimized splice is suspected to create uncontrolled modal content for the seed signal. With the used signal coupling, the increased gain did not increase the beam quality, as one might expect based on [4].

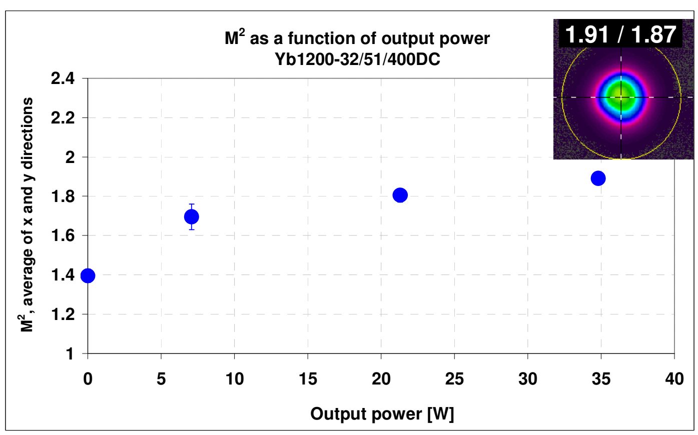


Figure 10. M^2 as a function of output power for the Yb1200-32/51/400DC. Output beam image at 35W shown in the inset.

4. DISCUSSION

According to simulations done in [4], a confined doped fiber should provide a good beam quality even with an imperfect input signal due to preferential gain for the fundamental mode. The results obtained from both the step index fiber and the tailored index fiber did not support this finding. During the writing of this paper, the authors were, however, not aware if the launching conditions used in the experiment were comparable to the starting values described in [4]. Further work should be conducted to either provide better launching condition for the amplifiers, or to better characterize the modal content of the seed.

This work did not include coiling of the confined doping LMA fibers to diameters less than 16cm. Any tight coiling should induce mode crunching, which in turn should result in higher nonlinearities due to the smaller mode field area [10]. The benefits or drawbacks of the step index vs. the tailored index fibers need to be studied, once the launching conditions of the amplifiers can be controlled or properly characterized by known methods [11, 12].

In this work the refractive index profile was tailored to enhance the coiling properties of the fiber, and the doping was confined in the middle-part of the fiber to provide preferential gain for the fundamental mode. During this work it became evident that the technical capability to tailor the gain profile would also be available, if required.

5. SUMMARY

Manufacturing of Yb-doped large-mode area fibers with confined doping and tailored refractive index profiles was demonstrated using the Direct Nanoparticle Deposition process. In addition, passive tower-drawn fiber LMA tapers applicable as mode field adapters were introduced. A power amplifier setup was constructed to characterize the active fibers and fiber tapers. Near diffraction-limited beam quality was achieved at the output of a taper fiber, where the core diameter was 40µm and the core NA 0.068. Compared to a conventional fiber amplifier with a 25µm core, a significant reduction in nonlinearities was observed when the seed signal was amplified using a 44µm confined-doped core fiber. The beam quality results that were obtained indicated a multimoded signal output. This was attributed to the unoptimized splice between the output of the taper and the input of the active fiber. In order to obtain comparable results the seed launching conditions need to be more carefully controlled. Further work is needed to optimize the dopant and refractive index profiles, NA and core diameter of the novel fibers for different applications and coiling diameters.

ACKNOWLEDGMENTS

The members of the fiber manufacturing team at nLIGHT Oy, Lohja, are acknowledged for their work on manufacturing the core material, subsequently shaping it into a preform, and drawing it to fiber. We also thank the fiber quality assurance team for their support on the fiber related measurements.

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