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# Large mode area double clad ytterbium-doped tapered fiber with circular birefringence

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## ABSTRACT

We demonstrated, for the first time to our best knowledge, an active tapered double clad fiber with circular birefringence and 35  $\mu\text{m}$  core diameter. The output radiation had perfect beam quality ( $M^2=1.18/1.1$ ) and linearly polarized light with 15 dB of PER. The developed double clad active fiber was investigated for amplification of picosecond pulses in all-fiber MOPA system. The MOPA system delivered 50 ps pulses with 55 W of the average power revealed 34.4 dB gain of the booster amplifier.

**Keywords:** fiber laser, active spun fiber, active tapered fiber, ultrafast fiber amplifier

## 1. INTRODUCTION

Technology of active double clad fibers (T-DCF) has been developing rapidly during last decade<sup>1,2</sup>. Similar to low numerical aperture large mode area fiber (NA LMA), large pitch fiber (LPF) and 3C fibers, active T-DCF represents LMA fibers with relatively high NA and a record-breaking core size (up to 100  $\mu\text{m}$ ), at the same time maintaining a single-mode propagation regime. The large core size significantly increases the threshold of nonlinear effects and allows to extract high peak/average power. Numerous active fiber-optic devices comprising T-DCF have been already demonstrated: kW-class CW single mode fiber lasers<sup>3,4</sup>, high gain and high-power CW amplifiers<sup>5</sup>, ultrafast picosecond amplifiers<sup>6,7</sup>, high power superfluorescent sources<sup>1</sup> and narrow band fiber amplifiers and lasers<sup>8</sup>.

The early works implemented the capabilities of the T-DCFs technology by utilizing the fibers without internal birefringence<sup>1,3,4,5</sup>. Recently, the family of scientific works has increased by experimental demonstration of the passive and active anisotropic tapers with an elliptical core of 70  $\mu\text{m}$  size<sup>9</sup> and stress rods (PANDA type)<sup>7,8</sup>. To date, the PANDA type of the active T-DCF are the most common to maintain the polarization of the linearly polarized light. However, despite of the fact that the technology of PANDA type fibers is well-developed and widely-used, complexity of the preform manufacturing process and strong mechanical stresses still remain the serious drawbacks of the method. Especially, it becomes more important for the large core area of T-DCFs.

The PANDA type fiber is not a unique approach to create birefringence in the fiber. By twisting preform during a fiber drawing process, it is possible to form the stresses, which support a propagation of polarized light. The fibers fabricated by this method are so-call spun fibers<sup>10</sup>. The spun fibers are extensively utilized for sensing applications<sup>11</sup>. They have an internal circular birefringence, and they are not sensitive to the orientation of launched linearly polarized light. The spun fibers approach is less time-consuming, simpler and cheaper. Therefore, they are good alternative technology for polarization-maintaining high-power fiber amplifiers.

In the present work, we, for the first time to our best knowledge, experimentally demonstrated the active ytterbium doped tapered fiber with internal circular birefringence (spun T-DCF, or sT-DCF). We exploited the fabrication method for the large core active fibers and investigated their polarization and amplification properties. The all-fiber picosecond MOPA system based on the Yb-doped spun tapered fiber was successfully realized for the first time.

## 2. SPUN TAPERED Yb-DOPED DOUBLE CLAD FIBER

### 2.1 Basic optical properties of sT-DCF

For manufacturing of sT-DCF we used a step-index Yb-doped preform, which index profile is shown in Figure 1a. The in-core absorption value was equal to 650 dB/m at 976 nm, and the numerical aperture was 0.1. The preform was assembled with core-cladding-diameter ratio (CCDR) equaled to 8. The sT-DCF was drawn by utilizing the similar technology used previously for a passive spun type fiber<sup>12</sup>. The fiber drawing process was performed with continuous variation of the drawing speed to obtain the fiber tapering, at the same time the preform was rotated with the constant velocity. The fiber was tapered down from 800  $\mu\text{m}$  to 125  $\mu\text{m}$  of outer cladding diameter along the length of 5 m. The profile of sT-DCF is shown in Figure 1b. In order to improve the double clad absorption, the preform was truncated four times. The end face image of the sT-DCF fiber obtained from the wide side is depicted in Figure 1b (inset). The clad absorption in the sT-DCF was 12 dB for 976 nm pump wavelength.

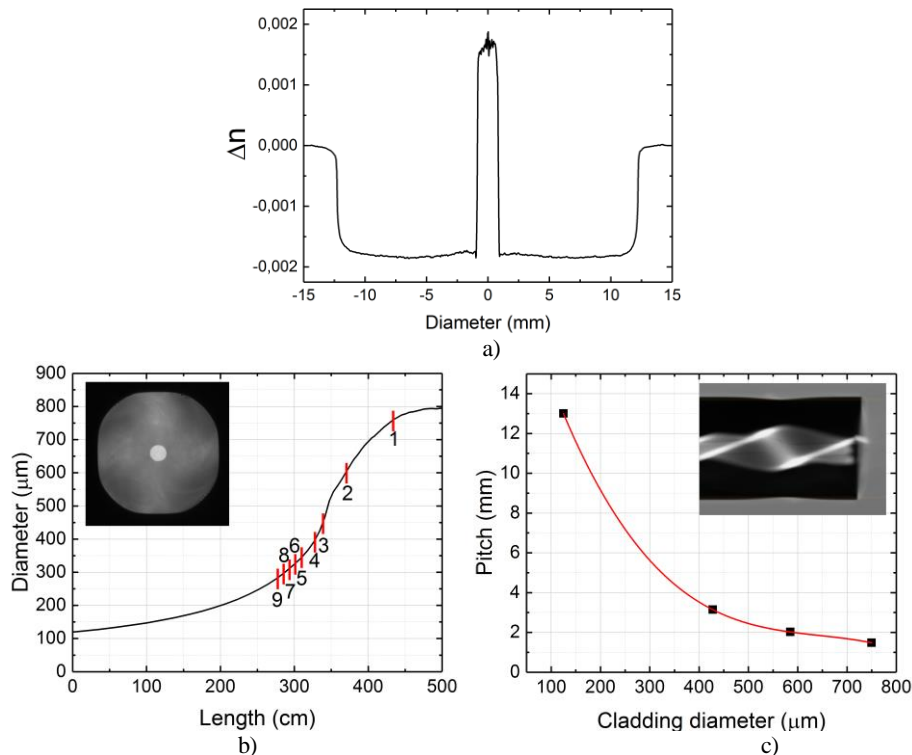


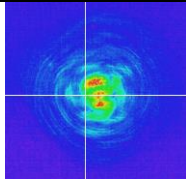
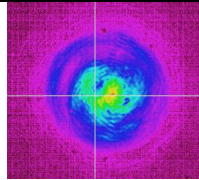
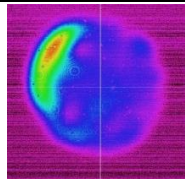
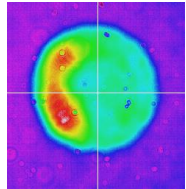
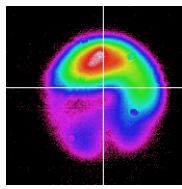
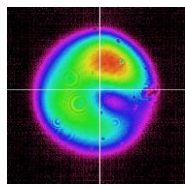
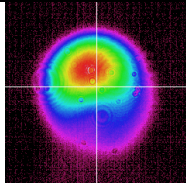
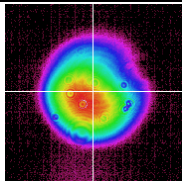
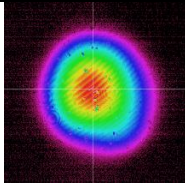
Fig. 1. a) Refractive index profile of the preform; b) The variation of outer cladding diameter with the sT-DCF length. Inset: end face image of the drawn fiber; c) The pitch as a function of the cladding diameter. Inset: the side view of the spun taper.

Since the drawing speed of the taper varied during the process, the pitch changed along the length of the sT-DCF simultaneously with tapering of the fiber diameter. The measured dependence of the pitch versus the clad diameter of the tapered fiber is presented in Figure 1c. The pitch of sT-DCF increased from 2 mm at the widest side part till 13 mm at thinnest fiber diameter. Figure 1c (inset) demonstrates the side view of the spun fiber at the wide part with the pitch equaled to 2 mm. The variation of the pitch along the sT-DCF length also led to the change of the local birefringence.

### 2.2 Output beam profile parameters

In the experiment, we investigated the dependence of the output beam shape on the core diameter of sT-DCF. For this, we sequentially shortened the taper from the initially drawn core/cladding diameter of 100/800  $\mu\text{m}$  down to 35/280  $\mu\text{m}$ , and measured the mode field distribution and  $M^2$ -parameter of the output beam. The results are summarized in Table 1.

Table 1. Output beam shape and  $M^2$ -parameter of the beam quality as a function of the core/cladding diameter.

|                              |   |  |   |
|------------------------------|---|--|---|
| Length, cm                   | 430   | 370  | 340   |
| Core/cladding, $\mu\text{m}$ | 95/760  | 75/600   | 56/450  |
| $M^2$ -parameter             | —   | —  | —   |
| Near field beam shape        |    |    |    |
| Length, cm                   | 330   | 310  | 300   |
| Core/cladding, $\mu\text{m}$ | 50/400  | 42/340   | 41/325  |
| $M^2$ -parameter             | —   | 1.93/2.02  | 1.84/2.13   |
| Near field beam shape        |    |    |    |
| Length, cm                   | 290   | 280  | 275   |
| Core/cladding, $\mu\text{m}$ | 39/310  | 36/287   | 35/280  |
| $M^2$ -parameter             | 1.85/1.88   | 1.21/1.33  | 1.18/1.10   |
| Near field beam shape        |  |  |  |

The output beam was strongly distorted due to the torsional mechanical stresses when the core/cladding diameter exceeded 56/450  $\mu\text{m}$  (Table 1). With decreasing of the core/cladding diameter down to 50/400  $\mu\text{m}$ , the beam became single-mode, but moon-shaped, and it was pushed off the core centre towards to the side. Each further step of the fiber reduction led to the improvement in the beam shape and  $M^2$ -parameter. Finally, the beam became round-shaped and filled the most area of the fiber core when the core/cladding diameter reached value of 35/280  $\mu\text{m}$ , (Table 1). These core/cladding dimensions corresponded to 6 mm of the pitch as seen from Figure 1c. At these parameters, the output of sT-DCF in amplification regime had a near diffracted limited pure fundamental mode with  $M_x^2 = 1.18$  and  $M_y^2 = 1.10$  (Fig. 2a).

In order to measure the physical size of the beam, we took two shots using CCD beam profiler. The first one was the image of the end face of the fiber without pumping, so that the core was visible and measurable. The second one depicted the output beam in the amplification regime and its profile. After that, we compared these two pictures side by side and estimated a mode field diameter at the level of 13.5%. Following this technique, we obtained the mode field diameter equaled to 26  $\mu\text{m}$  for the sT-DCF with 35/280  $\mu\text{m}$  cladding (Fig. 2b). Thus, the MFD occupied 75% of the core.

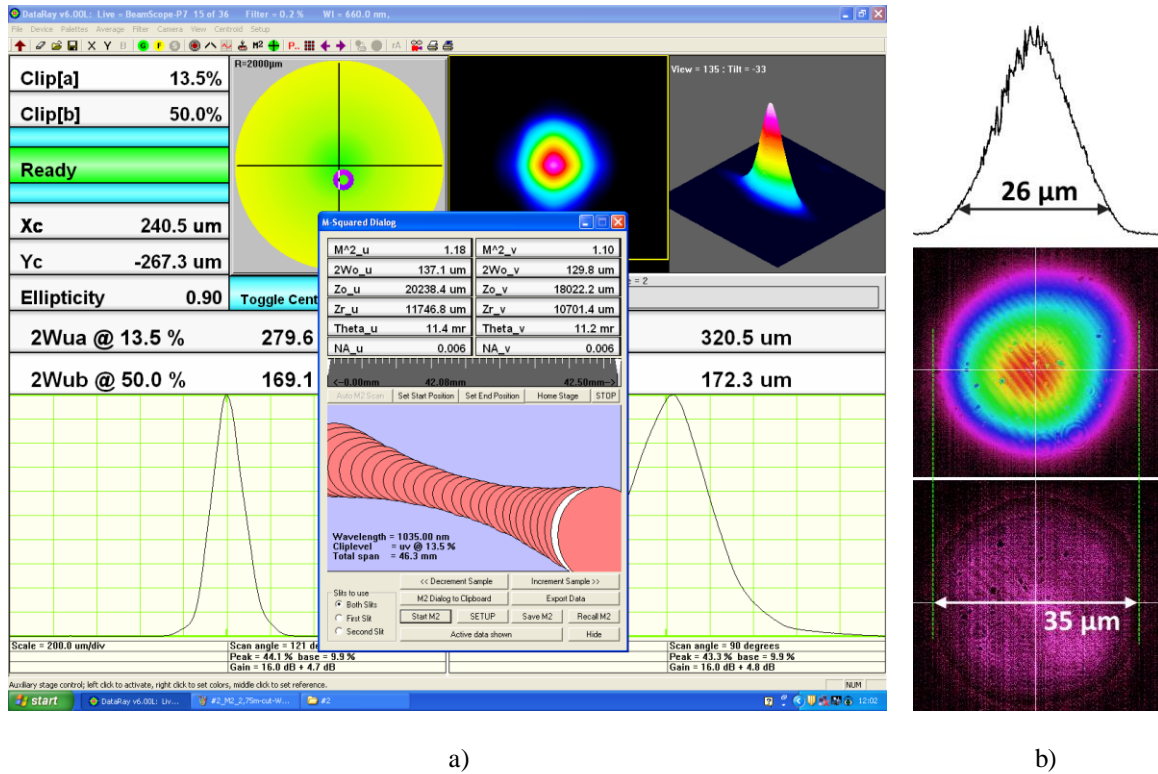


Fig. 2. a)  $M^2$  measurement for sT-DCF with 35/280 μm core/cladding dimensions; and b) its core and beam size at the level of 13.5%.

### 3. PICOSECOND MOPA WITH sT-DCF

To investigate the sT-DCF polarization and amplification properties, we built an experimental setup of all-fiber MOPA system shown in Fig. 3. The co-propagating pump and signal were launched into the narrow side of sT-DCF via the pump combiner. A high-power isolator was used to protect the seed laser from back reflections that could cause a damage or introduce instabilities. The counter-propagating pump was injected through the dichroic filter and focusing lens. We used 27 W and 80 W wavelength stabilized laser diodes for pumping from narrow and wide sides. The active spun tapered fiber was wound with a diameter of 35 cm and set in the metal grooves with water-cooling.

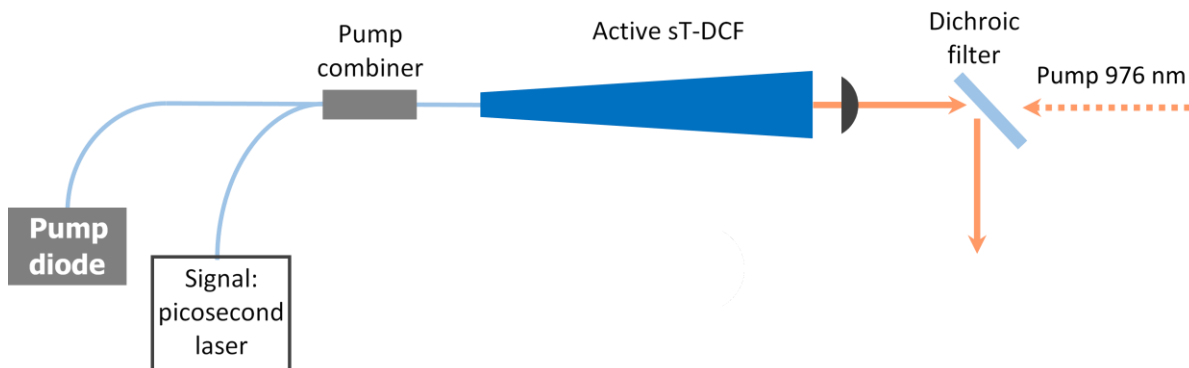


Fig. 4. The experimental setup of all-fiber MOPA system with sT-DCF.

### 3.1 Polarization properties

The polarization properties of the sT-DCF in amplification regime was examined by using a commercial PM pigtailed gain-switched diode from PicoQuant GmbH. The PM laser diode were characterized by a central wavelength of 1064 nm and a spectrum width (FWHM) of 40 pm (Fig. 4). The repetition rate of the seed source could be tuned from 1 MHz to 80 MHz. For our experiments, we used the repetition rate of 80 MHz, because it provided the highest output power of the signal (approximately 2 mW). Higher repetition rate was also beneficial to minimize amplified spontaneous emission, which could deteriorate the results of PER measurements. The pulse duration was equal to 80 ps. The polarization extinction ratio of the signal launched into a sT-DCF was measured as high as 15dB.

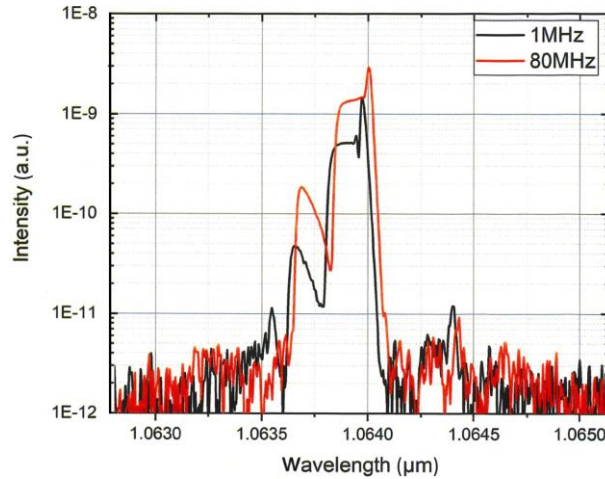


Fig. 4. The spectrum of the 1064 nm seed laser at repetition rates of 1MHz and 80MHz.

The spatial uniformity of polarization and polarization extinction ratio of the output beam in amplification regime were studied in the following experiment. For a qualitative assessment of the spatial uniformity of the amplified radiation, we set a Glan-Taylor polarizer in front of the beam profiler and took a series of shots at different azimuth of polarizer. Figure 5a shows the intensity distribution of the output beam in the near field zone after passing through the polarizer for four different orientations of the polarizer (at 0, 30, 60, and 90 degrees). The upper row series belongs to sT-DCF length of 340 cm; the bottom series belongs to tapered fiber length of 275 cm.

In both cases, the beam intensity decreased uniformly with rotation of the polarizer, which indicated that the beams were single-mode and polarization was uniform across the core. This confirmed our assumption that, although strong internal stresses distorted and displaced the beam relatively the core center, it retained the launched single-mode properties until the core diameter reaches 56 µm.

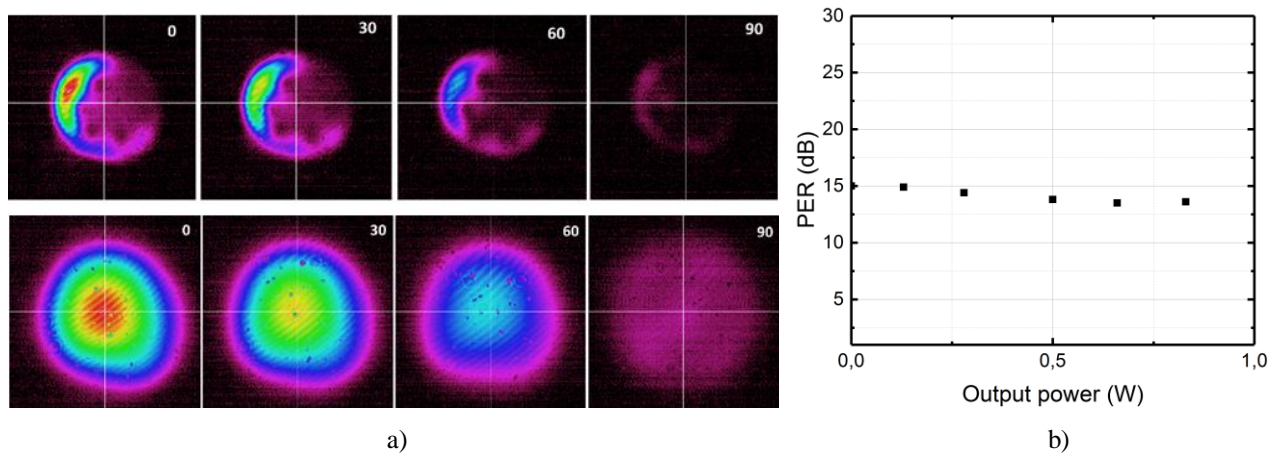


Fig. 5. a) The beam shape versus azimuth of polarizer, b) Polarization extinction ratio versus output power.

The polarization extinction ratio of the output beam was measured using Glan-Taylor polarizer and power meter. We placed the power meter after the polarizer and measure the output power for two cases: 1) when azimuth of polarizer coincided with polarization vector of the beam, and 2) when angle between them was equal to 90 degrees. Then PER parameter was calculated by the formula  $PER=10\lg(P_1/P_2)$ . We also investigated the dependence of the output power on the PER value. The data were presented for the output power within the range from 0 to 0.83 W determined by the power meter limit (Fig. 5b). The sT-DCF output was linearly polarized with PER ranging from 14 to 15 dB at the constant value of PER for the input signal equaled to 15 dB. The state of polarization remained linear, although the extinction decreased slightly with increasing of the output power (Fig. 5b). In this experiment, we were also limited in terms of the output power because of low input power of the PM seed laser. A further increase of the pump power led to a growth of spontaneous emission, and as a result, a degradation of PER, since spontaneous emission always exhibited non-polarized property.

### 3.2 Amplification properties

The amplification properties of sT-DCF were investigated by utilizing another fiber-based seed laser. Mode-locked laser delivered 4.2 nm spectrum width at the central wavelength of 1035 nm. The laser emitted 50 ps pulses with repetition rate of 14.8 MHz. This seed laser was favorable for testing of the sT-DCF amplification properties due to higher output power (20 mW) and broader spectrum, which allowed extracting of more energy from the amplifier.

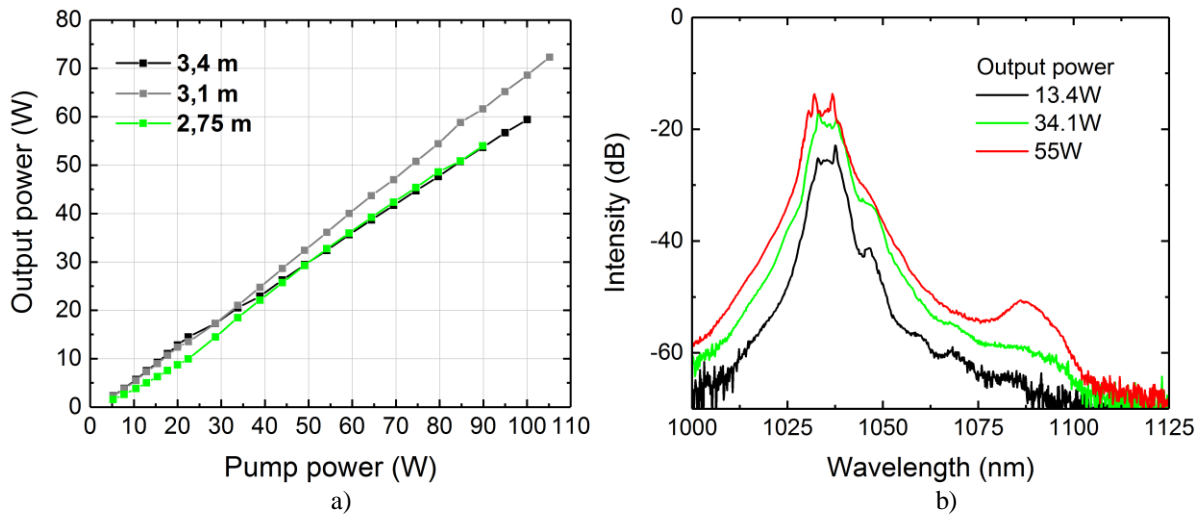


Fig. 6. a) signal output power versus pump power (in comparison of different sT-DCF's lengths), and b) spectra of the output signal at different output power levels.

We measured the amplification properties for fiber samples with three lengths: 3.4 m, 3.1 m, 2.75 m (Fig. 6a). Since the earlier results revealed the good quality of the beam for the maximum length equaled to 2.75 m, we provided the detail description only for the experiment with this particular sample.

At the first stage, the sT-DCF was pumped only through the narrow side via pump combiner by wavelength-stabilized diode operated at 976 nm. We launched 22 W pump power from the narrow side and reached 10 W of the output power with slope efficiency equaled to 45% (Fig. 6a, green line). At the second stage, the sT-DCF was additionally pumped from the wide side by 80 W diode. The pumping scheme was realized through dichroic filter, and the light was coupled to active fiber via focusing lens. The maximum output power was 55 W, what corresponded to the efficiency of 61% and 34.4 dB gain. The Figure 6b illustrates the corresponding spectra measured at different output power levels. At the maximum output power of 55 W, we recorded a slight broadening of the spectrum till 6 nm at 3 dB level.

As visible from Figure 6a, the sT-DCF length of 3.1 m had higher efficiency, about 69%. At the same time, 3.4 m long fiber had almost the same efficiency as 2.75 m long fiber. This could be explained by the fact that sT-DCF was very sensitive to the cleave angle. For example, with flat cleaves perpendicular to the length of the fiber, the output power

dropped by almost 2 times, and back reflections deteriorated the performance. Because of strong internal stresses and atypical geometry, it was difficult to produce an angle cleave of the optimal value.

#### 4. CONCLUSION

In conclusion, we have demonstrated at the first time, to the best of our knowledge, a spun active tapered double clad fiber. Experimentally, we investigated the influenced of the torsional mechanical stresses on the output beam shape and quality, and determined the optimum for core/cladding and pitch parameters equaled to 35/280  $\mu\text{m}$  and 6 mm, correspondingly. Since a larger modal field diameter is always desirable, in the future we are planning to investigate sT-DCF with a larger MFD and a pitch of 5 mm or less. The question of what pitch is optimal for large core requires further experimental study. Having a core diameter of 35  $\mu\text{m}$ , sT-DCF operated in a strictly single mode regime with excellent beam quality ( $M^2=1.18/1.10$ ) and demonstrated MFD of 26  $\mu\text{m}$ . The sT-DCF revealed good polarization-maintaining properties preserving the linear polarization of the input beam with minor degradation at higher output power. A new tapered fiber was utilized for high power amplification in all-fiber picosecond MOPA system delivered 4  $\mu\text{J}$ , 50 ps pulses with 55 W average power (34.4 dB gain).

#### 5. ACKNOWLEDGMENT

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