High Peak Power Er-doped Tapered Fiber Amplifier

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Abstract: A novel tapered Er^{3+}-doped fiber design for high peak power amplification has been developed and tested. The fiber core was based on P_2O_5-Al_2O_3-SiO_2 glass matrix, which allowed simultaneous achievement of low NA and high Er content. The core diameter was changing along the fiber length from 22.5 µm (single-mode operation) to 86 µm along 2.5 meters. Amplifier based on counter propagation signal (coupled to the thin tapered fiber end) and pump (coupled into thick fiber end) was developed and a nearly diffraction-limited beam quality ($M^2<1.27$) of the output signal has been achieved. Amplification of 80 ns single frequency Gaussian-shaped pulses has resulted in peak power of 20 kW in 55 ns pulses (1.5 mJ) limited by available pump power.

1 INTRODUCTION

High peak power laser sources at eye-safe spectral region near 1.55 µm are attractive for a variety of free space applications, such as remote sensing and LIDAR (LIght Detection And Ranging). In many cases (for example wind LIDARs (Kotov *et al.*, 2016)) pulses with duration from tens to hundreds nanoseconds with spectral width from several tens kHz to tens of MHz are required. In this case instability of amplified pulse caused by Stimulated Brillouin Scattering (SBS) is the main factor that limit maximum peak power (Kotov *et al.*, 2014).

Nowadays, cladding pumped Er-Yb co-doped fibers are used to obtain high average powers at 1.55 µm (Jeong *et al.*, 2005). However, efficient energy transfer from Yb to Er ions requires codoping of the fiber core with large amounts of phosphorus, which limits the diameter of the single mode core. Thus, in single-frequency regime up to 6.6 kW of peak power was demonstrated for multimode (M^2~5) Er-Yb fiber lasers (Codemard *et al.*, 2006) and up to 1.2 kW for single-mode regime (Shi *et al.*, 2010). In addition, parasitic Yb emission near 1 µm renders these lasers unsafe for free space applications.

Several Yb free Er doped large mode area cladding pumped at 976 nm fiber amplifiers were developed by our group recently. Pump to signal conversion efficiency of 40% in single-mode continuous wave (CW) regime was demonstrated (Kotov *et al.*, 2013). The record peak power of 4 kW before the stimulated Brillouin scattering (SBS) threshold for silica-based single-frequency single-mode all-fiber lasers was demonstrated (Kotov *et al.*, 2014).

Core pumping of Er-doped Yb-free fibers at 1.48 µm by a high power Raman lasers appears promising for obtaining high peak power due to reduced nonlinearity. Indeed core pumping reduces by few times the length of Er-doped used in amplifier compared to that in cladding pumped schemes. Moreover, single-mode pumping allows for nearly single-mode operation in multimode fibers, thus decreasing fiber nonlinearity (Jasapara *et al.*, 2009). Therefore, up to 1.1 kW of peak power before the SBS threshold was demonstrated in the single-mode regime using a 40µm core Er-doped

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fiber (Canat *et al.*, 2013). However, the main problem of this approach is a high complexity of the scheme, which results in a low overall signal-to pump conversion efficiency and a high production cost. Moreover it requires usage of high power 1480/1550 wavelength division multiplexers (WDMs), which are available as experimental samples only and are subject to rapid power degradation.(Peng *et al.*, 2013).

Utilization of tapered fiber geometry is a novel promising way to decrease fiber nonlinearity. The idea of this approach is simple: the core and cladding diameters monotonically increase along the fiber length to several times their original size. The fundamental mode excited at the single-mode (thin) end propagates towards the thick end of the tapered fiber adiabatically (without exciting higher order modes (HOMs)) (Jung *et al.*, 2009). Recently high peak power Yb-doped cladding-pumped tapered fiber amplifier was developed by our group (Bobkov *et al.*, 2017). Using this approach we demonstrated increase of the stimulated Raman scattering threshold for 28 ps pulses to the level of 760 kW, which is an order of magnitude higher compared to non-tapered Yb doped cladding-pumped fiber amplifier (57 kW) (Kalaycioglu *et al.*, 2010).

In the present paper we utilized the tapered fiber approach for the case of Er-doped fibers. Amplification of 80 ns pulses to peak power of 20 kW is demonstrated using Er-doped tapered cladding-pumped at 976 nm fiber amplifier.

2 TAPERED FIBER DESIGN AND FABRICATION

2.1 Preform Fabrication

The preform was made by Modified Chemical Vapour Deposition technique. Similar to (Kotov *et al.*, 2015), the fiber core was made of P_2O_5-Al_2O_3-SiO_2 (PAS) glass matrix which allows for higher concentration of Er^{3+} ions due to lower clustering. Moreover, simultaneous doping of the fiber core with P_2O_5 and Al_2O_3 leads to formation $AlPO_4$ join, which has refractive index nearly equal to that of pure silica glass. The core was doped with ~0.14 mol.% Er_2O_3 and had numerical aperture (NA) of 0.076. In addition, we utilized so-called W-shaped refractive index profile (RIP) – a depressed fluorine-doped layer was placed just outside the core (see Figure 1). It reduced cut-off wavelength for the core with a fixed diameter. This allowed us to achieve single-mode propagation regime in a slightly bent thin tapered fiber end having outer diameter of 90 μm (cut-off wavelength~1.7 μm)

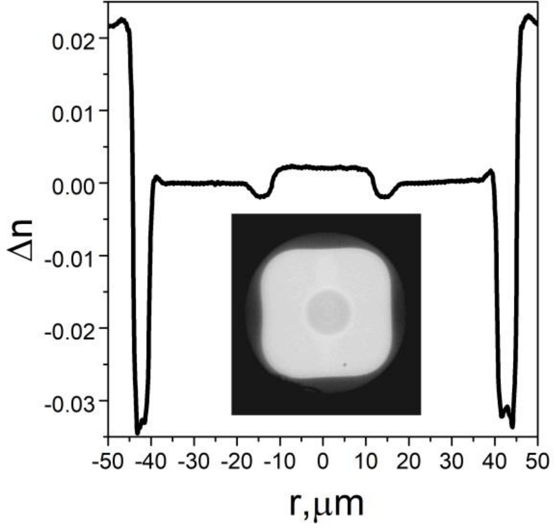

Figure 1: RIP of drawn fiber with outer diameter of 90 μm and optical image of fiber end facet.

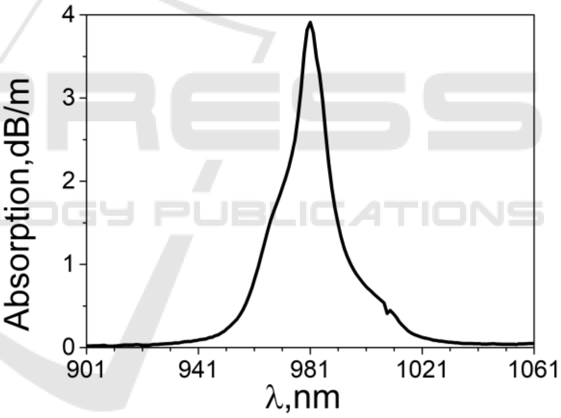

Figure 2: Small signal absorption from the cladding measured by cutback technique.

Fabricated preform was polished to square shape to ensure better overlap between cladding pump modes and the fiber core. After that, preform was overcoated with a fluorine-doped silica layer having NA ~ 0.3. Core to the average first cladding diameters ratio was 1/3, which also increased pump absorption from the first cladding – small signal absorption at 981 nm was about 3.9 dB/m (see Figure 2). Another important advantage of the F-doped silica cladding was the simplicity of preparing the thick end, which could be glued into an adapter and angle-polished using standard equipment. Thus, a perfect angle-cleaved thick fiber end compatible with a high power end-pumping technique could be routinely obtained.

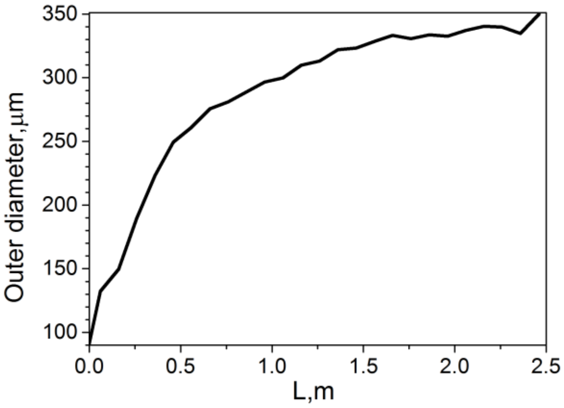

Figure 3: Tapered fiber outer diameter along the length.

2.2 Fiber Drawing

To produce the tapered fiber, we utilized a non-stationary fiber drawing process. This method was proposed and realized for the first time at FORC RAS in 1991 (Bogatyrev *et al.*, 1991), When it was used to draw relatively long (10-1000 m) tapered fibers. Later, this method was modified to draw short (~1 m in length) tapered fibers (Bogatyrjov and Sysoliatin, 2001). After additional modifications, the non-stationary fiber drawing process allowed us to obtain a highly reproducible set of few tens tapered fibers with a variation in the parameters of less than 10%, with a tapered region length of less than 1 meter and a tapered ratio up to 7. The diameter distributions of outer diameter over the fiber length for a tapered fiber cut from such a drawing are presented in Figure 3. The maximum outer diameter was 350 µm (core diameter of 86 µm), the fundamental mode field diameter (MFD) was estimated to be 53.4 µm (mode field area ~ 2240 μm^2) at 1550 nm.

A smooth enough transition between the thin and the thick ends of the tapered fiber is required to avoid excitation of HOMs during propagation of fundamental mode to the thick end. Since our geometry is similar to (Bobkov *et al.*, 2017) with lower difference between diameters of thin and thick ends and longer taper length, we could expect that fundamental mode propagates adiabatically in our case too. This feature was checked by measurements of M^2 at the output of the developed Er-doped tapered fiber in continuous wave operation regime. The measurements were done with a Thorlabs M2MS-BP209IR2/M measurement system and shows the perfect beam quality – M^2 was equal to 1.26/1.27 for x/y axis (see Figure 5).

3 AMPLIFICATION OF 80 NS PULSES

3.1 Experiment Setup

Experiment setup is presented in Figure 4. Distributed feedback laser diode (DFB-LD) with central wavelength of 1555.6 nm, output power of 1 mW and linewidth of 2 MHZ was used a seed source. Its radiation was coupled into semiconductor optical amplifier (SOA) through a polarization controller (PC) driven by two channel arbitrary waveform generator (AWG) to produce 80 ns pulses with repetition rates of 1 kHz and average power of 0.5 µW. The polarization controller was necessary due to SOA being polarization dependant and DFB-LD being based on non-polarization maintaining fiber. Resulting pulses were amplified by Er-doped fiber amplifier (EDFA1) core pumped at 980 nm. Since input power was far below saturation level of EDFA1 we used single circulator (C1) with long fiber Bragg grating (FBG1) with spectral linewidth of 0.08 nm to filter out amplified spontaneous luminescence (ASE) obtaining 230 µW of average power (~3 W peak power). “Clean”, pulses were amplified by second Er-doped core-pumped at 980 nm fiber amplifier (EDFA2). Another circulator (C2) with long fiber Bragg grating (FBG2) with spectral linewidth of 0.08 nm were used to filter out additional ASE and protect EDFA2 from backscattered light from tapered fiber amplifier.

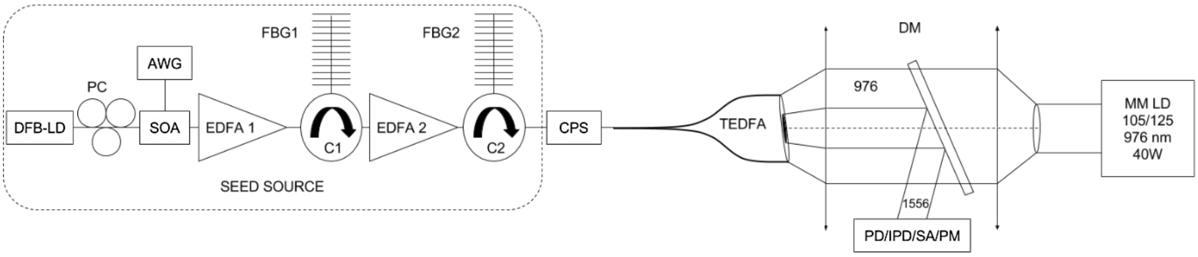

Figure 4: Experiment setup.

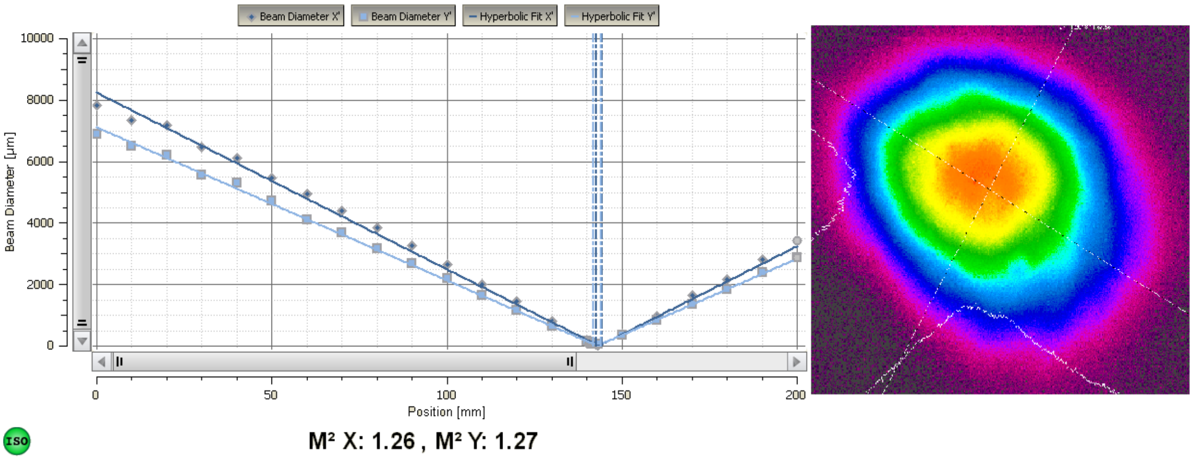

Figure 5: M^2 measurements and beam intensity distribution in far field.

Up to 50 W peak power pulses (4 mW average) limited by SBS in EDFA2 were coupled through cladding pump stripper into tapered fiber amplifier (TEDFA). It was pumped with wavelength-stabilized (976±1 nm) multimode pump diode having 105/125 delivery fiber (NA ~ 0.15). Dichroic mirror was used to separate amplified light at 1555.6 nm from pump at 976 nm. The end facet of TEDFA was angle cleave at ~7^{o} to prevent backscattering. Photodiode (PD), integrating photodiode (IPD) (Kotov *et al.*, 2015), spectrum analyser (SA) and power meter (PM) were used to characterize amplified pulses.

3.2 Results

Amplification of 80 ns pulses with repetition rate of 1 kHz resulted in 1.63 W of average power. Part of power contained in ASE was controlled by IPD and SA. According to spectral measurements wide ASE peak near 1530 nm contained up to 3.5% of power at maximum pump power. Measurements by IPD indicate that up to 9% of power was contained between pulses at maximum pump power. Thus, we can conclude that up to 5.5% power consisted of amplified continuous radiation at 1555.6 nm. Pulse peak power and energy dependencies on pump power are presented at Figure 6. Discrepancy between energy and peak power at high pump powers is due to inversion depletion following propagation of the forward front of the pulse (see Figure 7). Obtained peak power of 20 kW (pulse energy of 1.5 mJ) in 55 ns pulses was limited only by available pump power. As up to 100W wavelength stabilized pump diodes are available now, the output power from the amplifier (and maximum peak power) can be significantly improved.

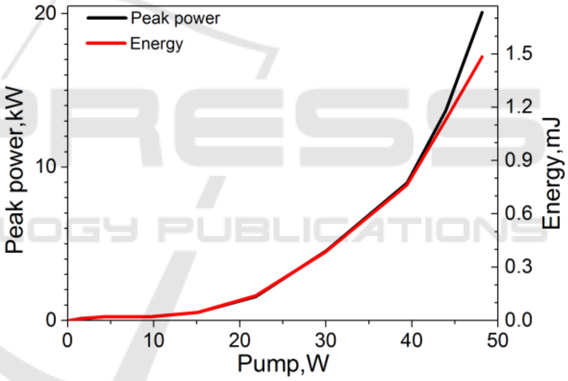

Figure 6: Peak power and energy vs pump power.

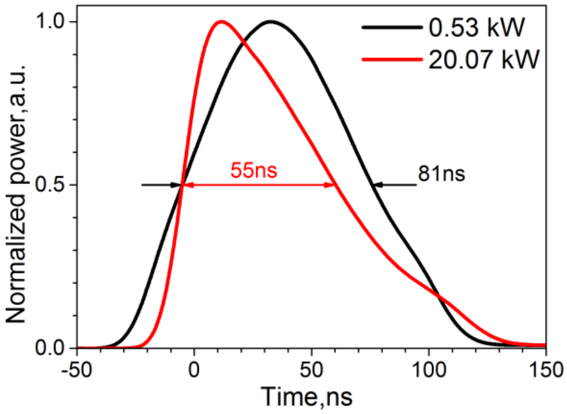

Figure 7: Temporal profiles at low and high pump powers.

4 CONCLUSIONS

We demonstrated amplification 80 ns pulses to up to 20 kW of SBS free peak power (1.5 mJ). The maximum peak power is limited by pump power available in our experiment and father power scaling using more powerful pump diode will be discussed at the conference.

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