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Generation of picosecond pulses with 150 W of average and 0.92 MW of peak power from an Yb-doped tapered fiber MOPA

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ABSTRACT

In this paper, we demonstrate possibility of simultaneous achievement of high peak and high average power in picosecond pulses using a monolithic amplifier based on a long Yb-doped tapered fiber. Due to a very high pump absorption (~ 25 dB/m at 976 nm) in the realized 2.4 m long tapered fiber most of the pump is absorbed near the thick tapered fiber end and a very small fraction of pump power reaches thin fiber end. As a result, signal passes through the thin part of the tapered fiber without an amplification and exhibits fast growth only near the output tapered fiber end, where a mode field diameter is large (35 µm at 1064 nm for 46 µm output core diameter), so that pulses can be amplified to a high peak power. Moreover, only a negligible fraction of pump radiation leaks at the conic part of the tapered fiber, because its most part was absorbed in the thick tapered fiber part. Thus a safe operation without polymer burning at a leakage point is possible up to a very high pump power. The developed tapered fiber was used in a final amplification stage of the all-fiber pulsed laser system, which allowed us to amplify 8.3 ps pulses with repetition rate of 18.4 MHz and central wavelength of 1064 nm to 150 W of average power and 0.92 MW peak power. The average power level was limited only by available pump power (230 W): no signs of transverse mode instability effects were observed.

Keywords: Yb-doped LMA fiber, high peak and average power, all-fiber megawatt system

1. INTRODUCTION

Fiber lasers, in particular ytterbium-doped, have a number of advantages such as the output beam diffraction-limited quality, high optical-to-optical efficiency and simplicity of design. Utilization of ultrashort pulsed fiber lasers for material processing attracts increasing interest nowadays. For this purpose, industry requires simultaneously high peak and average output power at short pulses (up to tens of ps) with high repetition rate to maintain high-speed and precise materials processing. However, the development of a such system in an all-fiber design with diffraction-limited beam quality is quite a challenging task. The main limiting factor for peak power scaling in fiber systems is a relatively low threshold of nonlinear effects such as stimulated Raman scattering, self-phase modulation and four-wave mixing. The threshold can be increased only by using of short-length large mode field area (LMA) fibers with an increased diameter of an active core. The main drawback of the approach is that the core of the most of LMA fibers also supports propagation of a few high-order modes, thus to realize singlemode operation regime some techniques have to be implemented: the differential modal gain regime [1] and, in some cases, the method of the selective excitation of the fundamental mode [2]. As a result, the maximum achievable average power level is limited by the onset of thermal effects leading to the output beam quality degradation caused by the waveguide structure change (thermally-induced refractive index change) or by the mode instability effect (a signal power coupling between the fundamental mode and the first high-order mode occurring on a thermal long-period grating induced by mode interference) [3]. In the paper [2] the record-high peak power level has been achieved with using of photonic-crystal fiber (PCF) with the core diameter of 108 µm and the length of 1.4 m with bulk optics signal/pump coupling/decoupling. Authors were able to amplify 3 ns pulses up to 1 MW of peak power at the fiber output, but the average power was only 10 W restricted by the onset of cladding modes amplification at higher level of average power. The same authors demonstrated amplification of 0.8 ns pulses up to 950 W of average power with only 15 kW of peak power by means of the step-index fiber (SIF) with the significantly smaller core diameter (mode field diameter of 27 µm) in bulky system [4]. However, the all-fiber system

based on the SIF with the 30 µm core diameter was able to generate pulses with 125 W of average power and only 15 kW of peak power at the fiber output [5]. Recently the amplification of 3 ns pulses up to simultaneously high peak power and high average power of 0.9 MW and 130 W, consequently, in the rod fiber with the core diameter of 100 µm in bulky system has been demonstrated [6]. In that case, further average power scaling was limited by the onset of the mode instability. To the best of our knowledge, the latter result is the record high for fiber systems. But the system consisted of a large number of bulk optics and high precision translators, thus it lacks of one of the main advantages of all-fiber systems – maintenance-free operation.

One of the promising LMA designs are the active tapered fibers. In such a design the core and the cladding diameters increase along the fiber length from a strictly singlemode core at the thin end, which can be easily spliced to conventional fibers to realize all-fiber system, and a several times larger in diameter core at the thick end. The smooth-enough increase of diameters ensures adiabatic increase of diameter of the fundamental mode propagating from the thin to the thick end of the fiber without excitation of the high-order modes [7]. Thus it can be expected that the tapered fibers can have less problems with TMI effect. In [8] the high-power single-frequency master oscillator power amplifier (MOPA) with the final stage based on a relatively long 18-m Yb-doped tapered fiber allowing an achievement of 160 W of average power has been demonstrated. In our previous paper [9] we have demonstrated the possibility of high-peak power (0.7 MW) achievement by means of tapered fiber that comparable with results demonstrated in PCF-based systems. However, in that work we were interested in obtaining pulses with only high peak power, so the average power level of our system was only 10 W. At the moment, the best result in terms of the obtaining of simultaneously high peak and average power by utilizing of tapered fibers was demonstrated in [10] where the fiber system generating 90 ps pulses with 28 W of average power and 292 kW of peak power has been realized. The main goal of the present paper is to investigate prospects of tapered fiber design for achievement of simultaneously high peak and average powers in picosecond pulses.

2.   EXPERIMENT

For this work we realized a series of ytterbium-doped polarization maintaining tapered fibers, the typical fiber had the length of 2.4 m and the core, the first cladding and the second cladding diameters of 46/330/410 µm, respectively, at the thick end of the fiber (Fig. 1, a). The small-signal absorption from the first cladding was measured to be ~25 dB/m at the wavelength of 976 nm (Fig. 1, b). Similarly to our previous work [9], the fiber had the all-glass design (see fiber cross section photo on inset at Fig. 1, a).
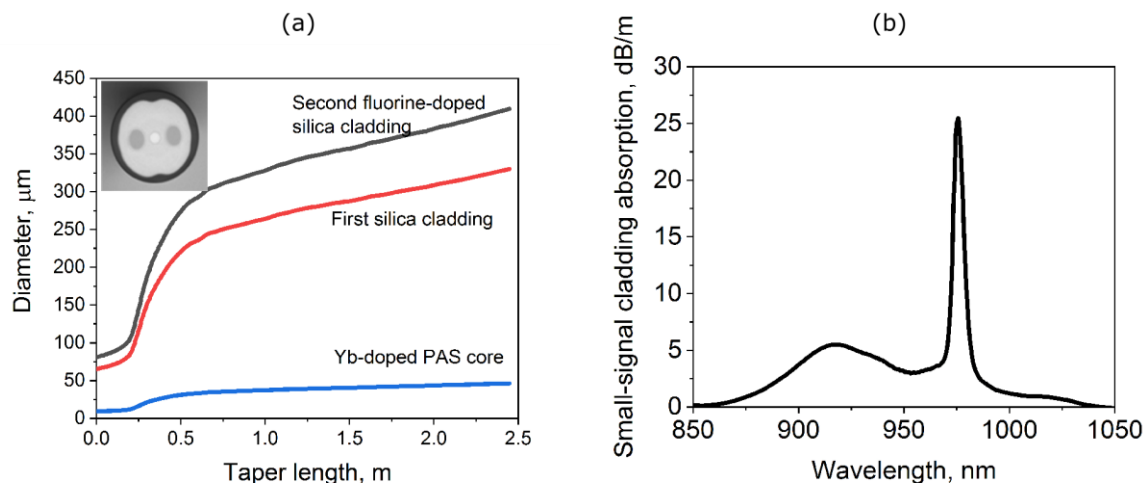

Figure 1. a) the dependence of the core, the first cladding and the second cladding on the length of the realized ytterbium-doped tapered fiber and the fiber cross section photo at inset; b) the spectrum of small-signal absorption from the first silica cladding.

With using of the tapered fiber in the final amplification stage the standard MOPA scheme was realized. As the master oscillator we used commercially available generator of 5 ps pulses with the central wavelength of 1064 nm from Fianium Ltd. These pulses were pre-amplified and stretched in a low-power part of the system and at the input end of the tapered

fiber a seed signal had an average power of 50 mW, a repetition rate of 18.4 MHz and a duration of 8.3 ps. The seed signal was coupled into the core of the tapered fiber by splicing the output fiber of low-power stage of the system to the thin end of the tapered fiber by means of a standard fusion splicer system. A pump radiation from three wavelength stabilized multimode diodes (two diodes emitting 100 W at numerical aperture of 0.15 and one diode emitting 45 W at numerical aperture of 0.15) from BWT Ltd. was summed up into one fiber by means of a 3 to 1 combiner and then coupled into the first cladding of the tapered fiber through the thick end utilizing two lenses (f=11 mm) and a dichroic mirror (HR@1064 nm and AR@976 nm). See Fig. 2 for set-up scheme.
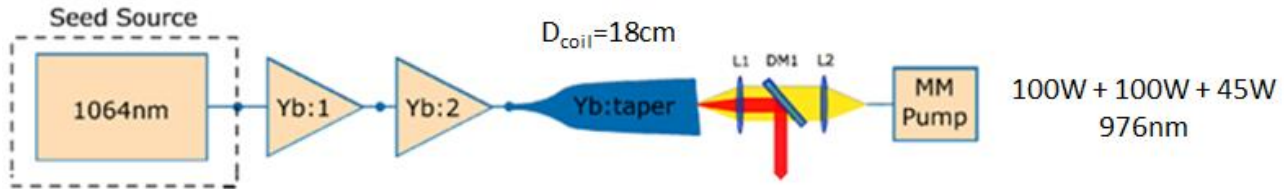

Figure 2. The realized MOPA scheme with the tapered fiber in the final amplification stage. Yb:1, Yb:2 are low-power core-pumped stages; DM1 is dichroic mirror; L1, L2 are lenses with f=11 mm.

2.1 Limiting factor for average power scaling

A main factor limiting average power scaling in a tapered fiber is the vignetting effect [11]. The vignetting is caused by the fact that the numerical aperture (NA) of a radiation that propagates along a tapered fiber from the thick end down to the thin end increases. In some point of a tapered fiber, obviously somewhere at transition region with rapid decrease in diameter, the radiation NA will exceed the guiding structure NA and the radiation will leak from the structure. That effect can have a positive impact on the small-signal gain value due to introducing high losses for the backward amplified spontaneous emission (ASE) [9]. But in the case of the pump radiation, the power of which is orders of magnitude greater than the power of the backward ASE, the leakage of radiation at some point of a tapered fiber can damage it via the heating and degradation of its polymer coating.

The diameter of the guiding structure where the leakage should occur can be estimated from a relation (1):

$$D_{1stclad}(z) < \frac{NA_{input}}{NA_{max}} D_{1stclad}(L),$$ (1)

where NA_{input}, NA_{max} are numerical aperture of coupled radiation and guiding structure, $D_{1stclad}$ is diameter of guiding structure, z is longitudinal coordinate along the guiding structure and L is total length of the structure. The value of loss caused by the vignetting can be estimated from an equation (2):

$$\alpha_{vign}(z) = \frac{20}{\ln 10 \cdot D_{1stclad}(z)} \cdot \frac{dD_{1stclad}(z)}{dz},$$ (2)

The temperature of the leakage point is determined by a number of factors, including an absorption of fiber coating polymer and other surrounding materials. But to define the hottest leakage point one should take into account an unabsorbed pump power and a diameter of a tapered fiber that determines a surface area, through which the leakage occurs:

$$T(z) = C \cdot \alpha_{vign}(z) \cdot \frac{P_{pump}(z)}{D_{clad}(z)},$$

where the coefficient C is determined mainly by characteristics of materials surrounding a fiber, a heat removal efficiency and other parameters, but it is almost independent of a z coordinate.

In this work the tapered fiber was fixed on an aluminum cylinder with a diameter of 18 cm. Firstly, we have conducted an experiment in order to determine a maximum pump power that the tapered part of the fiber can handle, in other words – at which level of the pump power the leakage point burns in result of the vignetting effect. The most thermal sensitive component of the fiber is a protective polymer coating – we used one designed to operate at temperatures as high as 85 ^{0}C. To find its thermal capabilities under laser radiation, we have shortened one of the tapered fibers down to 0.8 m in length so that the pump radiation absorption in a part of the fiber from a coupling point down to the leakage point becomes negligible and almost the all coupled pump power reaches the leakage point. Thus we determined a maximum allowable operational temperature of the polymer heated by the leaked laser radiation. During the experiment we controlled the temperature of the leakage point by means of a thermal viewer (Fig. 3). The experiment showed that the polymer burns at the temperature of 110 ^{0}C corresponding to 110 W of pump power.

It worth to clarify that in a longer tapered fiber almost all the pump power will be absorbed in the thick part before reaching the leakage point, thus the maximum coupled pump power and, therefore, the maximum output signal power will be considerably higher than that in the abovementioned experiment. To estimate the maximum coupled pump power in the tapered fibers with different length (from 0.8 to 2.4 m) the theoretical model, considered the power of signal, pump, forward and backward amplified spontaneous emission and the first Raman stokes and geometry of tapered fiber, from [9] was employed. As a criterion of the maximum coupled pump power we used a condition that the leakage point temperature should not exceed 40 ^{0}C that we supposed to be an "acrylate-friendly" temperature. According to abovementioned experiments, 40 ^{0}C corresponding to the coupled pump power of ~ 30 W, so in our simulations we were finding such value of input pump power that residual pump value does not exceed 30 W. From simulation data shown at Fig. 4 it seen that the maximum allowable pump power, being limited by the vignetting effect, as well as the obtained signal power grow exponentially up to ~1.7 kW and ~1.4 kW, correspondingly, with the increase of the tapered fiber length.
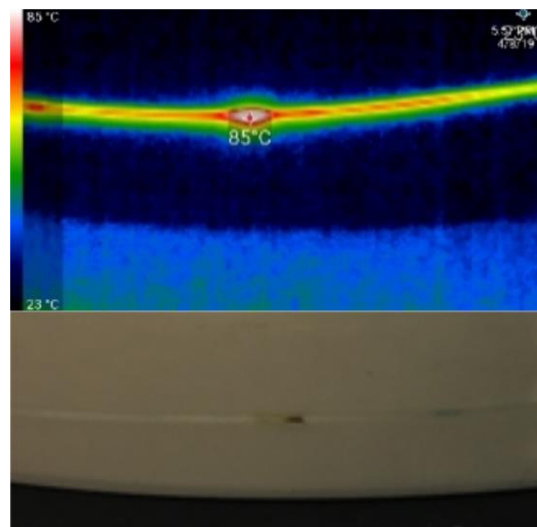

Figure 3. The thermal viewer photo of the leakage point at top and the photo of the leakage point after the polymer burning at temperature of 110 ^{0}C at bottom.
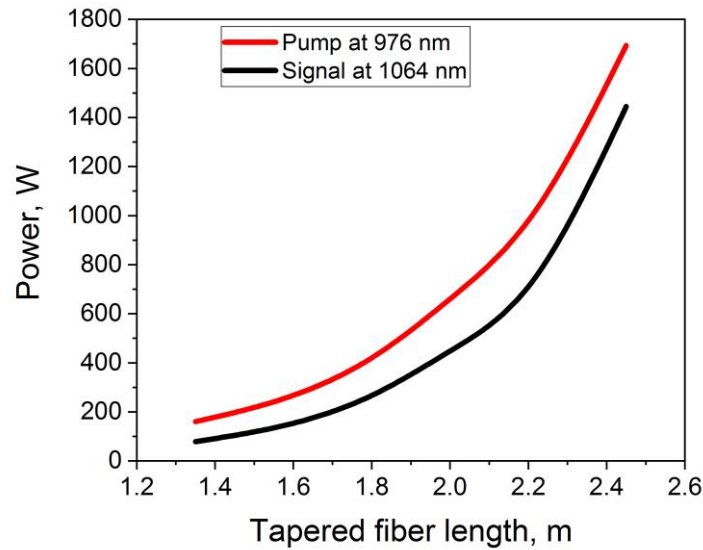
Figure 4. The dependence of the maximum theoretically-obtained signal power and the maximum theoretically-allowable pump power on the tapered fiber length.

2.2 Limiting factor for peak power scaling

It is well known, that for a regular fiber with constant diameters of the core and the cladding an increase of its length results in a decrease of the nonlinear effects threshold. For this reason, the previously mentioned method of the average power scaling of tapered fibers seems not to be optimal. However, in our last paper [9] it was shown that a choice of the 976 nm pump wavelength and the 1064 nm signal wavelength enables the operation regime in which the nonlinear effects threshold increase with a tapered fiber length. Such an unusual behavior can be explained as follows: the most part of the pump power is absorbed in the thick part of the fiber, while the thin part remains almost unpumped, so the whole amplification occurs only in the thick part with high mode field diameter.

2.3 Final experiment

A final series of experiments were conducted to test the theoretically obtained results. We do not have a few-kW pump power sources, but the available pump sources with total power of 250 W allow us to verify whether the tapered fibers can beat record-high result of 130 W average power and 0.9 MW peak power demonstrated with PCF in [6]. The used 2.4 m long tapered fiber in the same MOPA scheme from the previous experiments (the tapered fiber seed was 50 mW / 18.4 MHz / 8.3 ps) allowed the achievement of 150 W of average power with 99% of power in the pulse spectrum (Fig. 5, a). Assuming Gaussian pulse shape, an estimated pulse duration is 8.3 ps (see autocorrelation function on Fig. 5, b), that corresponding to 0.92 MW of peak power. In that regime the optical-to-optical efficiency was 68.7 % (see Fig. 5, c). Further average power scaling was limited by an available pump power. We also conducted an experiment on the mode instability effect threshold estimation by the method described in [12]: the obtained result shows no signs of the MI (no peaks at 0 – 5 kHz region excepting the fundamental one) (Fig. 5, d). Thus, the demonstrated result is better than previous record one, obtained by means of PCF [6].
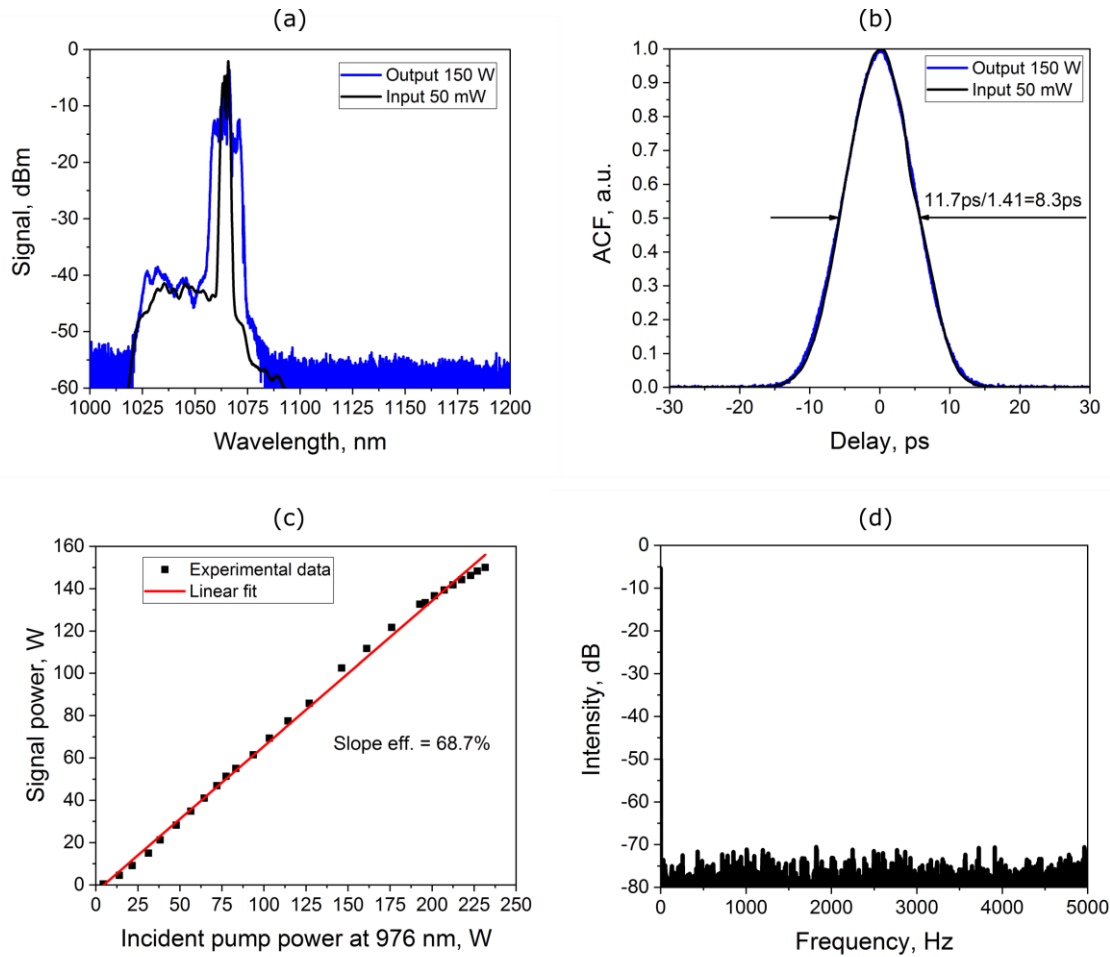
Figure 5. a) The spectra of the tapered fiber input and output signal; b) autocorrelation functions of pulses before and after the tapered fiber; c) the output signal dependence on the incident pump power; d) transverse mode instability effect measurements.

3. CONCLUSION

In conclusion, we have demonstrated the amplification of 8.3 ps pulses with 18.4 MHz repetition rate up to 150 W of average power and 0.92 MW of peak power with no signs of mode instability effect. To the best of our knowledge the reported result is record high for fiber systems. The average power level was limited by the available pump power source. Thus, a high prospects of a tapered fiber design for picosecond pulses amplification up to simultaneously high peak and high average power were demonstrated.

4. ACKNOWLEDGMENTS

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