meter-long tapered fiber. When a 1064 nm signal was used with the 1.05-meter tapered fiber, the threshold was somewhat higher than that of the 1.5-meter fiber, but in this case a large amount of ASE appeared at 1030 nm. A threshold of 300 ± 50 kW was estimated for the case with 4% ASE.

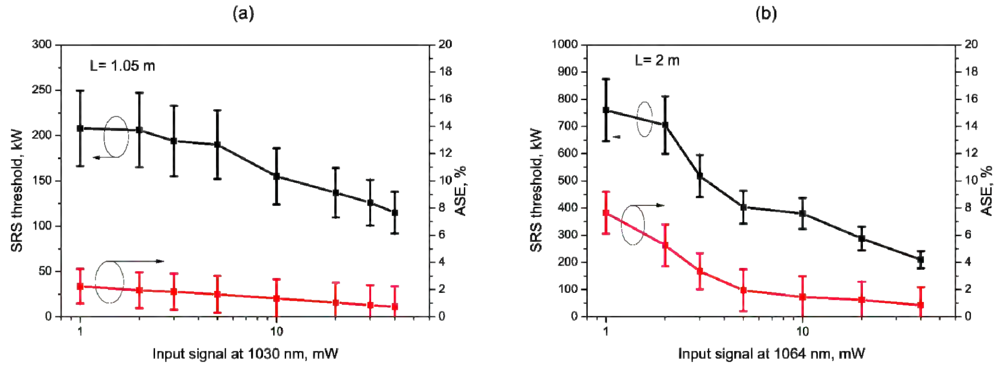

Fig. 6. The dependence of the SRS threshold and the ASE on the input signal power for a 1.05-meter tapered fiber operating at 1030 nm (a) and for a 2-meter tapered fiber operating at 1064 nm (b).

Table 2. The measured SRS thresholds for different lengths of tapered fibers and different signal wavelengths

Taper length, m	The measured SRS threshold value, kW	
	1030 nm@10 mW	1064 nm@10 mW
1.05	150 ± 50	300 ± 50
1.5	50 ± 20	250 ± 30
2	-	380 ± 60

In conclusion, a maximum SRS threshold of 380 kW was observed in the 2-meter-long tapered fiber with a 10 mW seed signal at 1064 nm, which agreed with our calculations. The amount of ASE in this case was below the accuracy of our measurements (2%). Moreover, the threshold could be further increased to 760 kW by reducing the seed signal power to 1 mW, but these conditions produced a large amount of ASE (7%) between the pulses.

4.4 Amplification of the chirped pulses

Finally, we conducted experiments on the amplification of chirped pulses centered at 1064 nm in the 2-meter-long tapered fiber. As a seed source, we used 100 fs master oscillator centered at 1056 with a full width at half maximum of 20 nm [29]. The pulses were stretched by propagation in 70 m of the commercially available passive polarization-maintaining fiber CS-98-3103 from 3M). To shift the pulse center wavelength to 1064 nm, we placed a bandpass filter with a 6 nm FWHM just before the "Yb:1" amplifier. Amplified pulses were compressed by a transmission grating compressor based on a pair of LSFSG-1000-3212-94 gratings from Lightsmyth. For pulse characterization, we used the well-known Second Harmonic Generation Frequency-Resolved Optical Gating (SHG-FROG) technique and, independently, the SHG Optical Autocorrelator (AC) Inrad 5-14B. The chirped pulse duration at the input to the tapered fiber amplifier was measured to be 28 ps. It should be noted that here and below, we consider only the final stage of the amplifier (i.e., that based on the tapered fiber); thus, by the input signal power, we mean the signal coupled into the tapered fiber.

During these experiments, we tried to find the optimal operational regime that gave high peak power directly from the amplifier and the possibility of further pulse compression. Thus, we needed to keep the SPM low to avoid severe deterioration the chirped pulse phase.

We conducted experiments at a relatively high repetition rate of 3.22 MHz. A 10 mW signal at 3.22 MHz was amplified up to an average power of 12.7 W, corresponding to a peak power of 141 kW. The spectra of the pulses at the tapered input and at the tapered output are depicted in Fig. 7(a). Then, these pulses were successfully compressed with 70% efficiency (an average power of 8.9 W after the compressor) down to 330 fs, which was confirmed by FROG measurements. The autocorrelation functions of the pulses before and after compression are shown in Fig. 8(b). The estimated peak power of the compressed pulses is 8.4 MW.

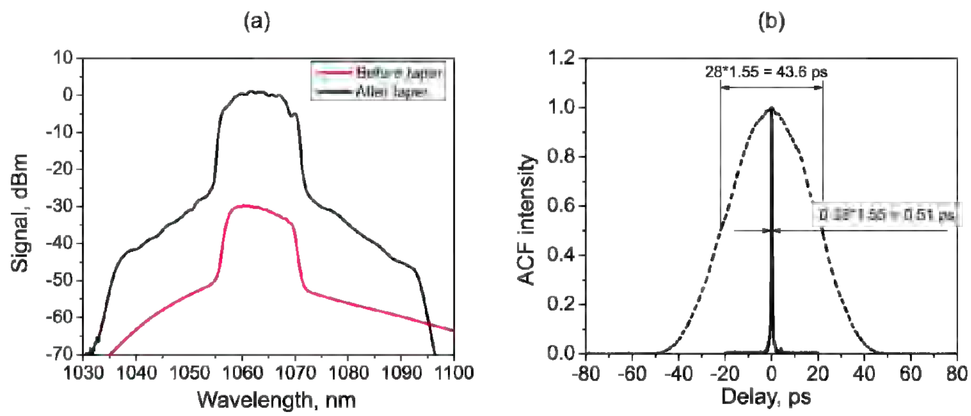

Fig. 7. (a) Spectra before and after the tapered fiber. (b) Autocorrelation functions for the pulse after the tapered fiber (dashed curve) and after the compressor (solid curve). The small peak to the right side of the ACF peak for the compressed pulses was due to a ghosting beam.

To confirm the obtained peak power, we observed the self-focusing (SF) effect in a BK7 glass rod. According to [30], the critical power for the SF effect in BK7 glass at 1064 nm is in the range of 3-4 MW. To observe the SF threshold, we placed, after the compressor, a half-wavelength plate, a polarizer (which was set for full transmittance of the beam), a lens with a focal length of 200 mm and a BK7 glass rod with lens focal point inside it. The half-wavelength plate was rotated to achieve the maximum transmission of the system, and we observed the SF effect at an average power of 8.9 W (i.e., ~8.4 MW of peak power, or much higher than the effect's threshold) (Fig. 8(a)). Then, we attenuated the beam by rotating the half-wavelength plate to see the threshold of the effect. The threshold was at 5.1 W of average power, corresponding to 4.8 MW of peak power (Fig. 8 (b)), which agrees with literature and independently confirms the estimated peak power of 8.4 MW.

Finally, we varied both the signal power and the repetition rate to find an optimal regime for pulse compression, whose quality is limited by the onset of self-phase modulation, which occurs much earlier than the onset of SRS. For all cases, the average power after the tapered fiber was 10 W, and the average power after the compressor was 8.3 W. We decreased the pulse repetition rate, thus increasing the pulse energy, and monitored the compressed pulse quality using FROG and the autocorrelator. The compressor length was slightly adjusted to compensate for the nonlinear phase shift. The estimated peak powers of the stretched 28 ps pulses after the tapered fiber were 0.11 MW for 3.22 MHz, 0.23 MW for 1.56 MHz, 0.35 MW for 1.03 MHz and 0.65 MW for 0.55 MHz. The measured autocorrelation functions (labeled with repetition rate/input average power), the FROG-retrieved compressed pulses, and the FROG-traces are shown in Figs. 9(a) and 9(b). The autocorrelation function for the compressed pulses at the tapered fiber output at a repetition rate of 3.22 MHz exhibited almost the same form as did those from the compressed seed pulses (at the input of the tapered fiber amplifier) (Fig. 9(a), green curve). The autocorrelation functions generated from the retrieved pulses agreed well with the measured ones. The pulses were successfully compressed at repetition rates as low as 1.03 MHz. The pulse duration of the FROG-retrieved pulses remained almost the same (in range of 315 ± 10 fs), whereas the pulse quality decreased slightly as a result of the increasing pedestal due to SPM. At 0.55 MHz, the nonlinear phase becomes too large, resulting in a significant uncompressed pulse pedestal and long wings in the autocorrelation function. The estimated peak powers of the FROG-retrieved pulses (with their real shapes considered) were 22 MW at 1.03 MHz, 15 MW at 1.56 MHz and 7 MW at 3.22 MHz. Thus, compression of the chirped pulses to a maximum peak power was limited by SPM in the tapered fiber amplifier at a peak power of 350 kW just after amplifier, which was only three times less than the record peak power achieved just after a PCF-based amplifier (before compression) in [1].

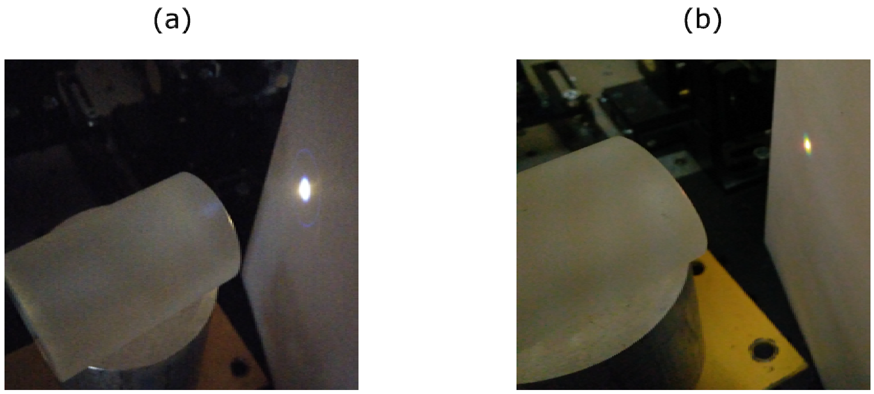

Fig. 8. (a) The observed self-focusing and supercontinuum generation effects at the peak power of 8.4 MW. (b) Self-focusing and supercontinuum generation effects at their threshold (4.8 MW).

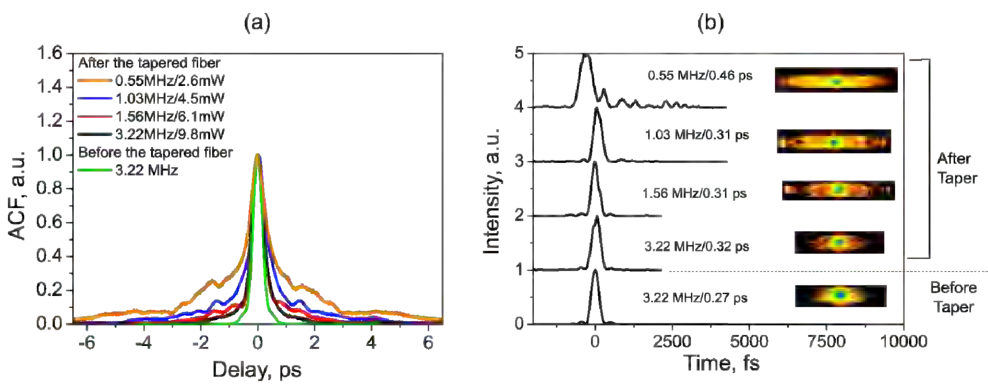

Fig. 9. (a) Autocorrelation functions for compressed pulses at different repetition rates and input powers, labeled as repetition rate/input average power. (b) The FROG-retrieved pulse duration and FROG-trace for the same repetition rates and input powers, labeled with repetition rate/pulse duration.

The obtained peak power in the compressed pulses was also indirectly confirmed by observing the self-focusing effect in the BK7 glass rod. Identical to the first experiment the SF was observed at the maximum power and then its threshold was measured by attenuating the beam using rotation of the half-wavelength plate. The SF thresholds were estimated to be 4.36 MW at 3.22 MHz, 5.1 MW at 1.56 MHz, 6.1 MW at 1.03 MHz and 4.7 MW at 0.55 MHz, which agree with literature and previously obtained threshold.

5. Discussion

In this paper, we presented an improved Yb-doped PM tapered fiber for high peak power amplification systems. During preliminary simulations, we revealed that the stimulated Raman scattering threshold increased with the length of the tapered fiber (up to 2 meters) and achieved its maxima for signal wavelength at approximately 1064 nm and pump wavelength at 976 nm. This unusual behavior was explained by a new amplification regime, when a signal propagated without amplification through most of the tapered fiber and experienced high gain only near the tapered fiber's output, where the fundamental mode has a maximum MFD.

During experiments, we confirmed our predictions and realized amplification pulses centered at 1064 nm with a peak power of up to 760 kW, which was limited by the SRS appearance (1% of power was in the 1st Stokes), and up to 350 kW when limited by SPM for chirped pulses. In the last case, pulses with duration of 28 ps were efficiently compressed down to 315 ± 10 fs with 70% efficiency. The demonstrated peak power at the amplifier output is about an order of magnitude higher than that demonstrated in the previous papers for monolithic (all-fiber) chirped pulse amplifiers [2, 10, 11]. Moreover, it is only three times less than the best value demonstrated with a PCF rod-type fiber [1]. Even this result can be further improved by increasing the tapered ratio. With the output core diameter of about 100 µm [14, 16] and a perfectly flat step-index core, the MFD at the thick end can be increased up to 70 µm (by factor of 2 relative to the results of this paper). In this case, one could expect the MW-peak power level for the chirped pulse amplification (which is comparable to the best value demonstrated with PCF [1]) and a few MW-peak power in the regime with a low ASE and a low 1st Stockes power.

Note that we demonstrated peak power of 22 MW in the compressed pulses, which is few times higher than the best values reported previously for monolithic amplifiers [2, 10, 11]. This value was limited by stretching/compressed ratio (~100) of our set-up and can be improved by an order of magnitude using a monolithic stretcher and a compact chirped volume Bragg grating compressor, similar to [2]. Thus, the maximum peak power after compression can be increased up to sub-GW level using the proposed concept of tapered fiber amplifier (by simple modification of the stretcher/compressor and by using a tapered fiber with improved parameters). This value is very close to the best results achieved with PCF [1], but in contract to PCF, the tapered fiber amplifier retains all the advantages of the all-fiber design, such as reliability, compactness and low production cost.

It is worth mentioning that achieving a high average signal power was not the primary goal of this paper and the average power of about 13 W obtained herein is far below the maximum value achievable with this type of amplifiers. Recently an average power of 120 W was demonstrated using an Yb-doped tapered fiber nearly identical (except for 1.5 times smaller output core and clad diameters) to the one presented in the current work [31].

6. Appendix: measurements of ASE level using integrating photodetector

The principle scheme of the "integrating photodetector" device is shown in Fig. 10(a). The investigated pulses were seeded into a 1 GHz photodetector, which charged the capacitor. The voltage at the capacitor was measured by an oscilloscope with 500 MHz bandwidth (in contrast to [17] we omit operational amplifier to reduce time response of the system). After each set of 8 pulses, the capacitor was shorted to ground. The measured voltage reflected the total optical power integrated over time. Shown in Fig. 10(b) is the case where CW radiation at 1064 nm with an average power of 1.5 mW was combined with pulsed radiation (8 ps, 1.03 MHz) with an average power of 3 mW in one fiber. The top graph depicts the dependence of power on time: the blue curve shows the case where only the pulsed source was turned on, and the red curve shows the case where both the CW and the pulsed sources were on. The bottom graph shows the obtained oscillograms. When only the pulsed signal was used, the capacitor charged only when the pulse reached the photodiode, resulting in a step-like oscillogram (blue curve). When CW (acting as the ASE) was also used, the capacitor was charged between pulses by CW signal, resulting in some charge accumulation between the steps (red curve). The CW part of the signal could be evaluated by measuring the h_1 and h_2 values and using a simple equation: $(h_1/(h_1+ h_2))*100\%$. We obtained a value of 34%, which was close to the real value of 33%. This technique allowed us to measure the amount of ASE in the output beam to within a few percent.

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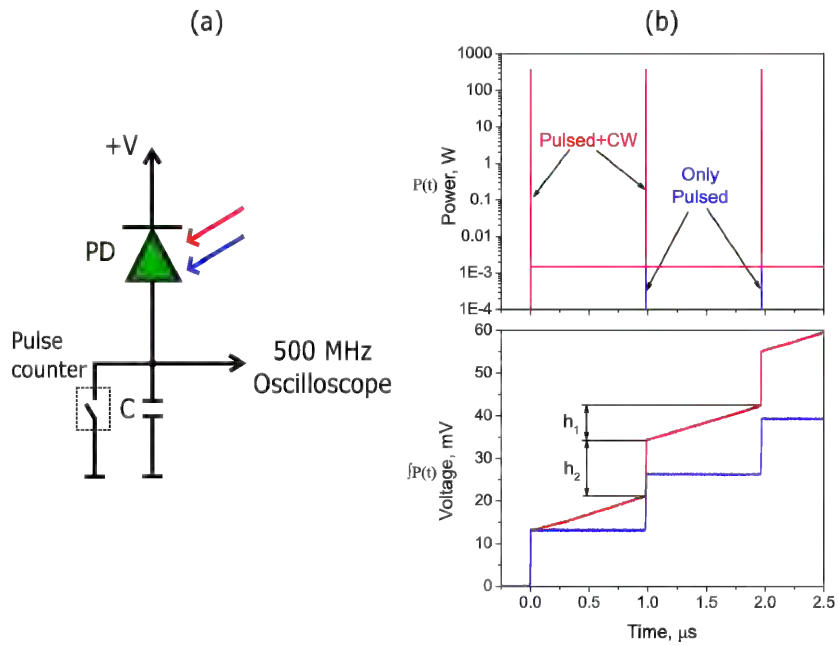

Fig. 10. The schematic and operating principle of the integrating photodetector. The data is obtained for 8 ps pulses at 1064 nm with a 1.03 MHz repetition rate and an average power of 3 mW combined with a CW signal at 1064 nm with an average power of 1.5 mW. PD is the photodetector, C is the capacitor.

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