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Long-Pulse Single-Frequency All-Fiber Amplifier

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Abstract

In this paper, we report a high power long-pulse single-frequency all-fiber amplifier at 1064 nm with near-diffraction-limited beam quality based on a polarization-maintaining tapered Yb-doped fiber (T-YDF). By applying square wave pulse modulation to the diodes, with a frequency of 50 Hz and a pulse width of 668 μs, the peak power of the output laser reached 257 W with an average power of 8.65 W, linewidth of 10.6 kHz and $M^2 < 1.5$.

Keywords

Long-Pulse, Single-Frequency, Fiber Laser, Stimulated Brillouin Scattering

1. Introduction

Single-frequency fiber laser is attracting more and more interest due to its wide application potential in gravitational wave detection (GVD) [1], coherent LIDAR [2], nonlinear frequency conversion (NFC) [3], coherent beam combining (CBC) [4] and so on. Due to the non-linear effects and transverse mode instability, such high-peak-power laser output is difficult to achieve via monolithic Single-frequency fiber lasers. The primary limiting factor in the power scaling process of single frequency fiber laser is usually considered to be stimulated Brillouin scattering (SBS) [5] [6] [7], which is known as the primary limitation factor of high-power single-frequency amplification, and could be suppressed by adopting a specially designed gain-tailored fiber [8] [9], a standard double-cladding large-mode-area (LMA) fiber with a high dopant concentration [10] [11] [12], a strain gradient [13], a temperature gradient [14], a tapered LMA fiber [15] and so on. Master oscillator power amplifier (MOPA) configuration is often employed for further power scaling, and several hundred watts of output power have been achieved.

In 2007, S. Gray *et al.* reported 500 Watts single-frequency fiber amplifier, where the SBS was suppressed by adjusting the composition of an Al/Ge co-doped gain fiber to reduce the interaction between acoustic and optical modes [16]. Yb^{3+}-doped fiber with core diameter of 39 μm and pump absorption coefficient of 3.2 dB/m was used to realize 502 W laser power while near single-mode operation with an M^2 of 1.4 was obtained due to the low core numerical aperture of 0.05. A record output power of 811 W has been realized by using a specially fabricated photonic crystal fiber, but not all-fiber structure and with a linewidth of 1.99 MHz [17]. In 2020, a 550-W single-frequency all-fiber amplifier at 1030 nm with tapered Yb^{3+}-doped fiber was reported [18], where gradually increased fiber core diameter provided a larger mode field diameter and a broadened SBS gain spectrum for higher SBS threshold. As for all-fiber single frequency fiber amplifier, 414 W linear-polarized output power has been reported by imposing strain gradient on a high-concentration PM LMA active fiber, the single frequency seed with linewidth of 20 kHz, and the linewidth of output laser not mentioned [19]. Moreover, the T-YDF has core/inner cladding diameters of 36.1/249.3μm at the input port and 57.8/397.3μm at the output port and the whole length is 1.27 m. However, the output laser has a resolution-limited linewidth of 45 MHz, when the linearly polarized single frequency seed is a fiber laser with linewidth of 20 kHz. Most of single frequency fiber laser focus on continuous laser output, and pulse laser output has been reported rarely. In 2019, a single-frequency 100 ns/0.5mJ pulses laser with a 5 MHz linewidth seed laser and tapered fiber with 50 μm diameter core in the output was reported, and reached 2.2 kW peak power with 18.7 dB polarization extinction [20].

Up to now, high power long-pulse single-frequency all-fiber amplifier is not reported, but that with high peak power and high energy is preferred in some coherent detection applications. In this manuscript, we demonstrate a long-pulse single-frequency all-fiber amplifier emitting at 1064 nm based on a high-dopant-concentration T-YDF. For diode-pumped monolithic fiber lasers, by applying square pulse modulation to the pumping diodes, we obtain a pulse laser output with a frequency of 50 Hz and a pulse width of 668 μs, the peak power of the output laser reached 257 W with an average power of 8.65 W, linewidth of 10.6 kHz and $M^2 < 1.5$.

2. Experiment Setup

The experimental setup is depicted in **Figure 1**, consisting of a seed laser and three-stage amplifiers. After an isolator, a 50 mW single-frequency linearly polarized seed laser with a center wavelength of ~1064 nm and a nominal linewidth of 1.8 kHz is injected into the first-stage amplifier. In the first-stage amplifier, a 2 m long PM single-cladding Yb-doped fiber (PM-YSF-HI-HP) with core/innercladding diameters of 6/125μm is utilized. Via wavelength division multiplexe, the active fiber is forward pumped by one 700 mW laser diode (LD)

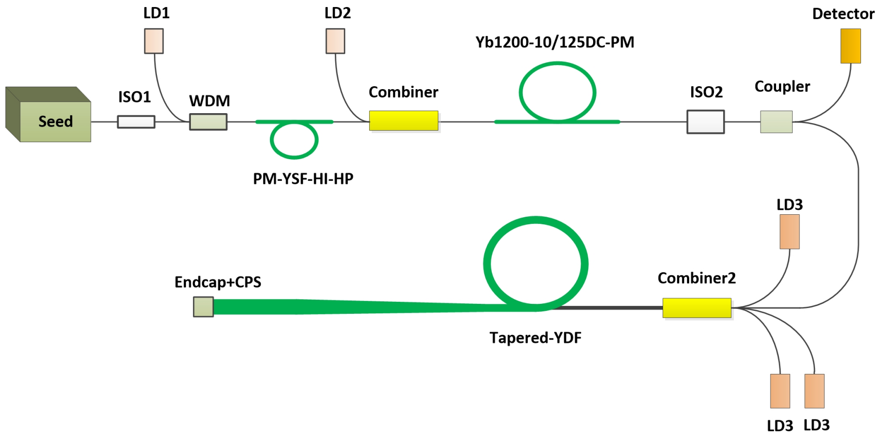


Figure 1. Experimental setup (ISO, isolator; LD, laser diode; WDM, wavelength division multiplex; YSF, Yb-doped single-cladding fiber; CPS, cladding power stripper; YDF, Yb-doped double-cladding fiber).

at 976 nm. The boosted signal light with a power of 185 mW is then launched into the second-stage amplifier after an isolator. Then the laser is launched into the second pre-amplifier utilizing a of 2 m long fiber (Yb1200-10/125DC-PM) with core/cladding diameter of 10/125μm. A 18 W laser diode (LD) with 976 nm central wavelength is used to pump the active double-cladding fiber via a (2 + 1) × 1 pump combiner, and applying square-wave pulse modulation to the diodes.

The power amplifier is pumped by three 120 W 976 nm LDs through a (6 + 1) × 1 signal-pump combiner, and applying square-wave pulse modulation to the diodes, with a frequency of 50 Hz and a pulse width of 668 μs, for example. In power amplifier, a polarization-maintaining tapered Yb-doped fiber (T-YDF) was used as shown in **Figure 1**. The T-YDF with a 976 nm absorption coefficient of 9 dB/m has core/inner cladding diameters of 35/250μm at the input port and 56/400μm at the output port, the whole length is 1.5 m and taper length is about 0.7 m. A cladding power stripper (CPS) is integrated in the output port of T-YDF to strip the residual pump light and ASE light, and an endcap is spliced behind CPS.

3. Experiment Results and Discussion

A plot of the signal average power versus pump power (the peak power of the output laser reached 257 W for an average power of 8.65 W) is shown in **Figure 2**, the output average power of the main amplifier has a 81.9% slope efficiency against pump power. It is found that the output beam has an excellent mode quality and demonstrates single-transverse-mode operation with $M^2 < 1.5$, which implies that the amplifier produced a near-diffraction limited output.

A seed oscillator with an SNR of ~50 dB is selected (as shown in **Figure 3**). However, compared with that of the seed oscillator, the SNR of the fiber laser is deteriorated to 45 dB due to the ASE noise. The spectrum of the backward propagating light was also recorded and is plotted in **Figure 4** for the cases of 4.71 and 8.65 Watts of forward output power. With only 4.71 Watts of output

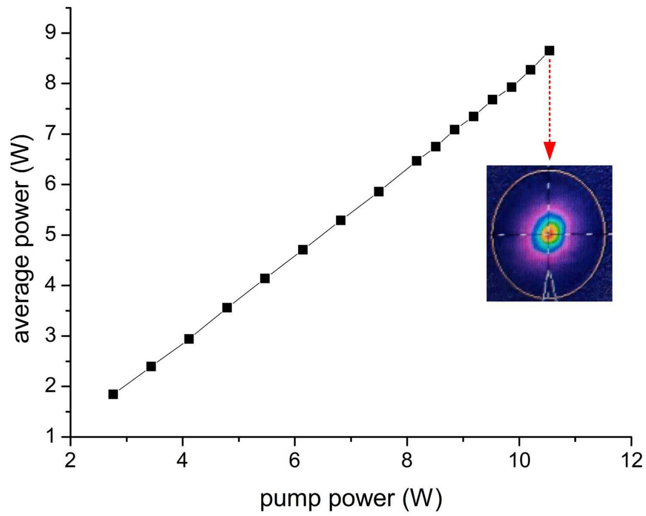


Figure 2. Signal versus pump power.

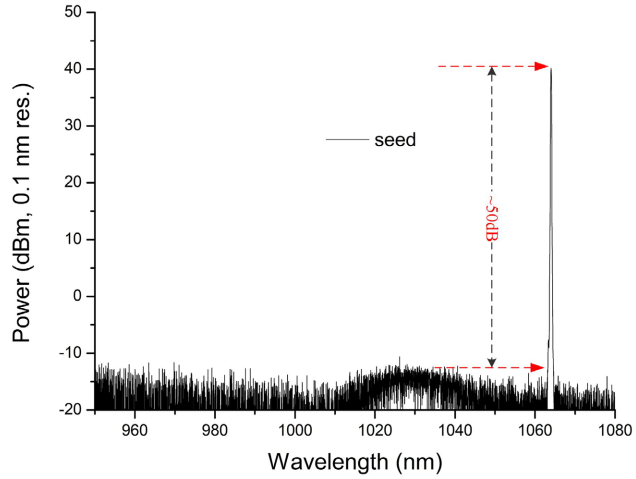


Figure 3. Spectra of light for seed.

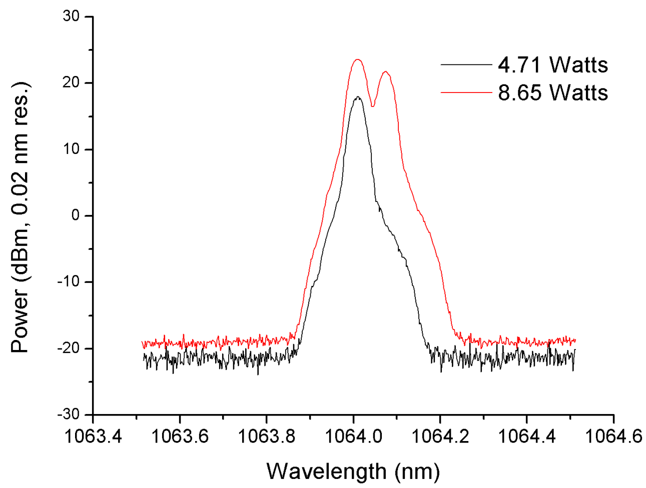
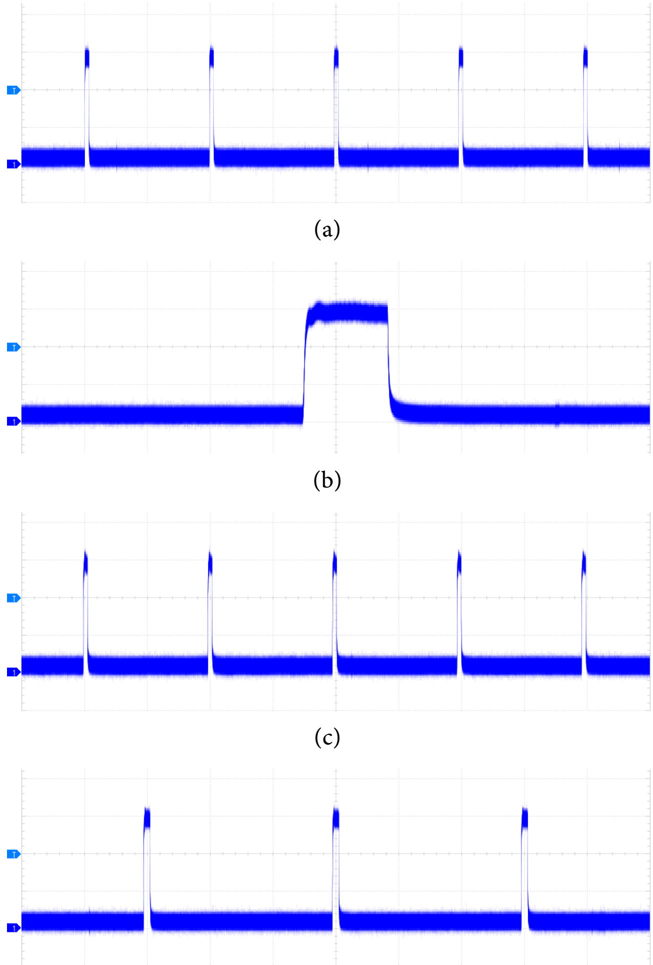


Figure 4. Spectra of backward propagating light for 4.71 Watt and 8.65 Watt average powers.



(a)

(b)

(c)

(d)

Figure 5. Pulse shape after power amplifier. (a) Pulses for multi-period with a frequency of 50 Hz and a pulse width of 668 μs; (b) Single-pulse shape with a frequency of 50 Hz and a pulse width of 668 μs; (c) Pulses for multi-period with a frequency of 100 Hz and a pulse width of 333 μs; (d) Pulses for multi-period with a frequency of 66 Hz and a pulse width of 512 μs.

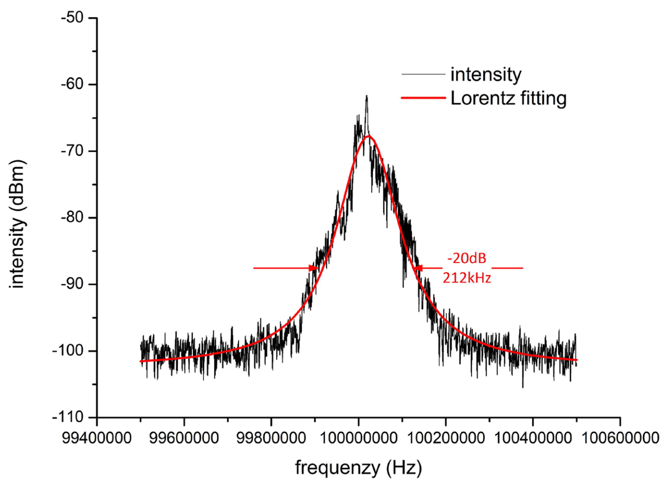


Figure 6. Measurement of laser linewidth for output laser.

power, the Stokes peak not exists. At 8.65 Watts of output power the Stokes peak is almost equal in magnitude to the spectra main peak, indicating a significant increase in the relative level of Brillouin scattered light.

For comparing, 1.5-m YDF (Liekki Yb1200-30/250-PM, Core NA of 0.062) with absorption coefficient at 976 nm is up to 10.2 dB/m is applied to long-pulse single-frequency all-fiber amplifier. The signal average power is up to 7.48 W, and the peak power of the output laser reached 217 W, that is lower than amplifier with active fiber T-YDF. T-YDF is proven to achieve high power single frequency output. This is due to the SBS frequency shift vary with the changed diameter of T-YDF [21], which results in a broadening SBS gain spectrum and can suppress SBS effectively.

By applying square wave pulse modulation to the LDs, the pulse shape of the output laser with a frequency of 50 Hz and a pulse width of 668 μs is shown in **Figure 5(a)** and **Figure 5(b)**. The frequency and pulse width could be adjusted in a wide range for application requirement, for a frequency of 100 Hz and a pulse width of 333 μs, or a frequency of 66 Hz and a pulse width of 512 μs, as shown in **Figure 5(c)** and **Figure 5(d)**. The pulse duty factor is almost no change when we adjust the frequency and pulse width, so the average power is almost no change, and the level of Brillouin scattered light is almost equal.

Measurements of laser linewidth are performed with a self-heterodyne method using a 60 km fiber delay. The fitting lineshape reveal a linewidth of 212 kHz with −20 dB from the peak of the Lorenz fitting line of optical beat signal at the maximum average power of 8.65 W, as shown in the **Figure 6**, which corresponded to a 3-dB laser linewidth of 10.6 kHz. The spectral linewidth appears some broadening than a laser linewidth of 1.8 kHz for seed oscillator, perhaps because nonlinear effects, such as self-phase modulation and four-wave mixing [22].

4. Conclusion

In conclusion, a high power long-pulse single-frequency all-fiber amplifier at 1064 nm with near-diffraction-limited beam quality based on a polarization-maintaining tapered Yb-doped fiber (T-YDF). Due to the non-linear effects, high-peak-power laser output is difficult to achieve via monolithic fiber lasers. By contradistinctive experiment, the T-YDF has more advantages of effectively suppressing Stimulated Brillouin Scattering (SBS) than large mode field YDF (Liekki Yb1200-30/250-PM). By applying square wave pulse modulation to the diodes, with a frequency of 50 Hz and a pulse width of 668 μs, the peak power of the output laser reached 257 W with an average power of 8.65 W, and $M^2 < 1.5$ in the two orthogonal directions, respectively. The linewidth of 10.6 kHz at the peak power of 257 W is broader than 1.8 kHz for seed oscillator, perhaps because nonlinear effects, such as self-phase modulation and four-wave mixing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Steinke, M., Tunnermann, H., Kuhn, V., Theeg, T., Karow, M., de Varona, O., Jahn, P., Booker, P., Neumann, J., Wesels, P. and Kracht, D. (2018) Single-Frequency Fiber Amplifiers for Next-Generation Gravitational Wave Detectors. *IEEE J. Sel.Top. Quantum Electron*, **24**, 1-13. https://doi.org/10.1109/JSTQE.2017.2759275

[2] Yang, F., Ye, Q., Pan, Z., Chen, D., Cai, H., Qu, R., Yang, Z. and Zhang, Q. (2012) 100-mW Linear Polarization Single-Frequency All-Fiber Seed Laser for Coherent Doppler Lidar Application. *Opt. Commun*, **285**, 149-152. https://doi.org/10.1016/j.optcom.2011.09.030

[3] Kumar, S.C., Samanta, G.K. and Ebrahim-Zadeh, M. (2009) High-Power, Single-Frequency, Continuous-Wave Second Harmonic-Generation of Ytterbium Fiber Laser in PPKTP and MgO:sPPLT. *Opt. Express*, **17**, 13711-13726. https://doi.org/10.1364/OE.17.013711

[4] Liu, Z., Ma, P., Su, R., Tao, R., Ma, Y., Wang, X. and Zhou, P. (2017) High-Power Coherent Beam Polarization Combination of Fiber Lasers: Progress and Prospect [Invited]. *J. Opt. Soc. Am. B*, **34**, A7-A14. https://doi.org/10.1364/JOSAB.34.0000A7

[5] Dawson, J.W., Messerly, M.J., Beach, R.J., Shverdin, M.Y., Stappaerts, E.A., Sridharan, A.K., *et al.* (2008) Analysis of the Scalability of Diffraction-Limited Fiber Lasers and Amplifiers to High Average Power. *Optics Express*, **16**, 13240-13266. https://doi.org/10.1364/OE.16.013240

[6] Kobyakov, A., Kumar, S., Chowdhury, D.Q., Ruffin, A.B., Sauer, M., Bickham, S.R. and Mishra, R. (2005) Design Concept for Optical Fibers with Enhanced SBS Threshold. *Optics Express*, **13**, 5338-5346. https://doi.org/10.1364/OPEX.13.005338

[7] Fu, S., Shi, W., Feng, Y., Zhang, L., Yang, Z., Xu, S., *et al.* (2017) Review of Recent Progress on Single-Frequency Fiber Lasers. *JOSA B*, **34**, A49-A62. https://doi.org/10.1364/JOSAB.34.000A49

[8] Pulford, B., Ehrenreich, T., Holten, R., Kong, F., Hawkins, T.W., Dong, L. and Dajani, I. (2015) 400-W Near Diffraction-Limited Single-Frequency All-Solid Photonic Bandgap Fiber Amplifier. *Optics Letters*, **40**, 2297-2300. https://doi.org/10.1364/OL.40.002297

[9] Mermelstein, M.D., Andrejco, M.J., Fini, J., Yablon, A., Headley III, C., Di Giovanni, D. J. and McCurdy, A.H. (2008) 11.2 dB SBS Gain Suppression in a Large Mode Area Yb-Doped Optical Fiber. *In Fiber Lasers V: Technology, Systems, and Applications. SPIE*, **6873**, 97-103. https://doi.org/10.1117/12.770346

[10] Ma, P., Zhou, P., Ma, Y., Su, R., Xu, X. and Liu, Z. (2013) Single-Frequency 332 W, Linearly Polarized Yb-Doped All-Fiber Amplifier with Near Diffraction-Limited Beam Quality. *Applied Optics*, **52**, 4854-4857. https://doi.org/10.1364/AO.52.004854

[11] Wang, X., Jin, X.X., Wu, W.J., Zhou, P., Wang, X.L., Xiao, H. and Liu, Z.J. (2015) 310-W Single Frequency Tm-Doped All-Fiber MOPA. *IEEE Photonics Technology Letters*, **27**, 677-680. https://doi.org/10.1109/LPT.2015.2390253

[12] Mermelstein, M.D., Brar, K., Andrejco, M.J., Yablon, A.D., Fishteyn, M., Headley, C. and Di Giovanni, D.J. (2007) All-Fiber 194 W Single-Frequency Single-Mode Yb-Doped Master-Oscillator Power-Amplifier. *LEOS* 2007*-IEEE Lasers and Electro-Optics Society Annual Meeting Conference Proceedings. IEEE*, 382-383. https://doi.org/10.1109/LEOS.2007.4382438

[13] Zhang, L., Hu, J., Wang, J. and Feng, Y. (2012) Stimulated-Brillouin-Scattering-Suppressed High-Power Single-Frequency Polarization-Maintaining Raman Fiber

Amplifier with Longitudinally Varied Strain for Laser Guide Star. *Optics Letters*, **37**, 4796-4798. https://doi.org/10.1364/OL.37.004796

[14] Jeong, Y., Nilsson, J., Sahu, J.K., Soh, D.B.S., Alegria, C., Dupriez, P., *et al.* (2005) Single-Frequency, Single-Mode, Plane-Polarized Ytterbium-Doped Fiber Master Oscillator Power Amplifier Source with 264 W of Output Power. *Optics Letters*, **30**, 459-461. https://doi.org/10.1364/OL.30.000459

[15] Shi, C., Fu, S., Deng, X., Sheng, Q., Xu, Y., Fang, Q., *et al.* (2022) 435 W Single-Frequency All-Fiber Amplifier at 1064 nm Based on Cascaded Hybrid Active Fibers. *Optics Communications*, **502**, 127428. https://doi.org/10.1016/j.optcom.2021.127428

[16] Gray, S., Liu, A., Walton, D.T., Wang, J., Li, M.J., Chen, X., *et al.* (2007) 502 Watt, Single Transverse Mode, Narrow Linewidth, Bidirectionally Pumped Yb-Doped Fiber Amplifier. *Optics Express*, **15**, 17044-17050. https://doi.org/10.1364/OE.15.017044

[17] Robin, C., Dajani, I. and Pulford, B. (2014) Modal Instability-Suppressing, Single-Frequency Photonic Crystal Fiber Amplifier with 811 W Output Power. *Optics Letters*, **39**, 666-669. https://doi.org/10.1364/OL.39.000666

[18] Lai, W., Ma, P., Liu, W., Huang, L., Li, C., Ma, Y. and Zhou, P. (2020) 550 W Single Frequency Fiber Amplifiers Emitting at 1030 nm Based on a Tapered Yb-Doped Fiber. *Optics Express*, **28**, 20908-20919. https://doi.org/10.1364/OE.395619

[19] Huang, L., Wu, H., Li, R., Li, L., Ma, P., Wang, X., *et al.* (2017) 414 W Near-Diffraction-Limited All-Fiberized Single-Frequency Polarization-Maintained Fiber Amplifier. *Optics Letters*, **42**, 1-4. https://doi.org/10.1364/OL.42.000001

[20] Patokoski, K., Rissanen, J., Noronen, T., Gumenyuk, R., Chamorovskii, Y., Filippov, V. and Toivonen, J. (2019) Single-Frequency 100 ns/0.5 mJ Laser Pulses from All-Fiber Double Clad Ytterbium Doped Tapered Fiber Amplifier. *Optics Express*, **27**, 31532-31541. https://doi.org/10.1364/OE.27.031532

[21] Shiraki, K., Ohashi, M. and Tateda, M. (1995) Suppression of Stimulated Brillouin Scattering in a Fibre by Changing the Core Radius. *Electronics Letters*, **31**, 668-669. https://doi.org/10.1049/el:19950418

[22] Kablukov, S.I., Zlobina, E.A., Podivilov, E.V. and Babin, S.A. (2012) Output Spectrum of Yb-Doped Fiber Lasers. *Optics Letters*, **37**, 2508-2510. https://doi.org/10.1364/OL.37.002508