Green picosecond narrow-linewidth tapered fiber laser system

V. Ustimchik[a, *], A. Fedotov[b], J. Rissanen[a,b], T. Noronen[a], R. Gumenyuk[b], Yu. Chamorovskii[c]
and V. Filippov[a]
[a]Ampliconyx Ltd, Lautakatonkatu 18, 33580 Tampere, Finland;
[b]Tampere University, Kalevantie 4, 33100 Tampere, Finland;
[c]Fryazino branch of Kotel’nikov Institute of Radio Engineering and Electronics, Vvedensky Sq. 1,
Fryazino Moscow region, 141120, Russia, Russian Federation
E-mail: vasilii.ustimchik@ampliconyx.com

ABSTRACT

We present a single-mode narrow band linear-polarized picosecond green fiber source delivered up to 146.4 kW of peak power. The laser architecture is composed of frequency-doubled all-fiber MOPA system operating at 1064 nm. The commercially available gain-switched semiconductor laser diode was used as a seed source delivered 77 ps pulses with the repetition rate between 100 kHz - 80 MHz. Two stages of pre-amplifiers based on the single-mode Yb-doped fibers were designed to amplify microwatt pulsed signal up to milliwatt level. A high-power amplification cascade comprised a double-clad polarization-maintaining tapered Yb^{3+}-doped fiber as a gain medium. The frequency doubling was realized in a single-pass scheme with LBO crystal. The MOPA design with the active tapered fiber enabled to amplify effectively a narrowband picosecond IR radiation with relatively small spectral broadening. We obtained stable laser radiation with 77 ps pulses at repetition rate of 1 MHz, 290 pm spectral bandwidth with a central wavelength of 532 nm, the average power of 12 W corresponding to 12 µJ of pulse energy and 146.4 kW of peak power. The overall efficiency of second-harmonic generation reached 37 % in a single pass scheme. The obtained results showed advantages of the MOPA system based on a tapered amplifier in comparison with already published picosecond green laser systems exploited standard amplifiers based on cylindrical fixed-core fibers. The single-mode green laser with high peak power and narrow line are in high demand for a wide range of Raman spectroscopy applications.

Keywords: green laser, high peak power, picosecond, narrow linewidth, frequency doubling, MOPA, linear polarized, singlemode tapered PM fiber

1. INTRODUCTION

A wide range of laser applications requires narrow spectral linewidth and small pulse duration with a high peak power level. One of the most demanding applications is Raman spectroscopy. This is a versatile technique, which provides a large number of analysis facilities employing in various fields of technology, mining, biology, medicine, and industry to determine chemical composition, flaw detection, inhomogeneity, etc. Raman spectroscopy is based on ultrafast Raman scattering response of material resulted in a small wavelength shift; therefore, this technique applies strict requirements to the laser source – high power and narrow spectral linewidth. Typically, continuous-wave green lasers based on second-harmonic generation from high power infrared MOPA sources are exploited in such systems. While the use of picosecond pulsed lasers instead of continuous-wave lasers in Raman spectrometers allows increasing the intensity of the scattering response of the material under test and significantly reducing the signal-to-noise ratio [1]. Such kind of time-resolved spectroscopy technique has been gaining interest over the past years as an important technique in a wide variety of fields [2-4]. To date, assemble of a narrow linewidth short-pulsed laser source with high peak power remains the actual problem of modern science. Recently published research results and commercially available products show peak power up to a few tens of kilowatt and full width at the half maximum of the spectral line more than 500 pm [5-7]. These systems do not fully satisfy the growing requirements of a tool for Raman spectroscopy. In this work, we demonstrate a fiber-based MOPA system delivered narrow linewidth picosecond radiation at 532 nm with up to 146.4 kW of peak power.

2. EXPERIMENTAL RESULTS

The green laser consisted of a frequency-doubled MOPA fiber system operating at 1064 nm was constructed as shown in Fig. 1.

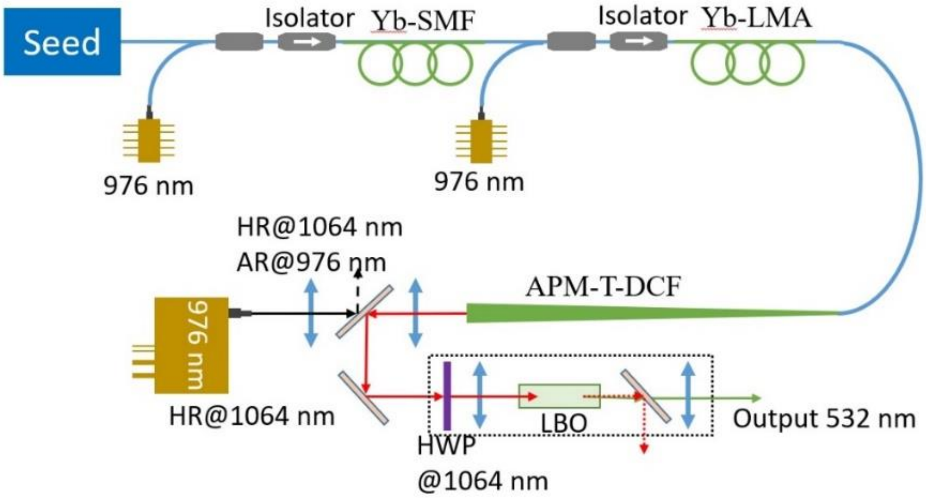

Fig.1. Optical Scheme of the MOPA system and second harmonic generation.

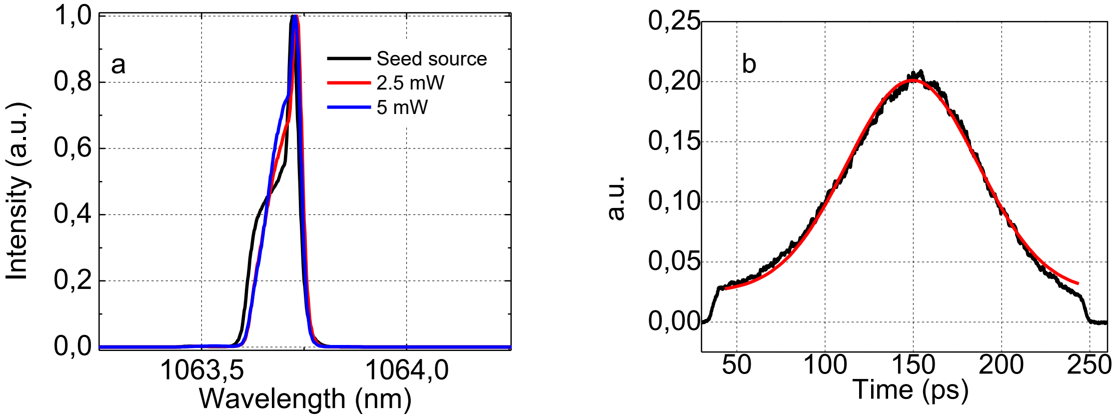

Fig. 2 (a) Spectra of fiber MOPA system: black line – seed source spectrum, red and blue line – amplified seed source spectrum with different levels of pump in the second cascade of amplification corresponding to 2.5 mW and 5 mW average output power of pre-amplifiers. (b) Seed source autocorrelation function.

The commercially available gain-switched semiconductor laser diode was used as a seed source. The seed source delivered picosecond pulses at repetition rates from 100 kHz to 80 MHz. Autocorrelation function of delivered signal is depicted in Fig.2. The full width of pulse autocorrelation function at half maximum was measured as 87.5 ps while Gaussian approximation was applied, which corresponds to the pulse duration about 77 ps. The average power of the seed source at 1 MHz repetition rate was 17 µW corresponding to 17 pJ of pulse energy. Full width at the half maximum of the spectral line was measured to be 56 pm (with spectrum analyzer resolution of 0.01 nm) depicted in Fig. 2. Two stages of pre-amplifiers were composed of single-mode 6-µm core and 10-µm core Yb^{3+}-doped fibers with co-propagating in-core pumping. The spectra measured directly from seed source and also after two amplification cascades is depicted in Fig. 2. Amplification in two stages of pre-amplifier did not change the seed source spectrum significantly. The pre-amplifier delivered up to 5 mW of the signal's average power at 1 MHz repetition rate, which was further coupled into a narrow part of the active tapered fiber. The red and blue line in Fig. 2 correspond to different pump levels in second pre-amplifier cascade. Tuning of the pump level in the second preamplifier cascade were used to reduce the influence of nonlinear effects (self-phase modulation and Raman scattering) while amplification in high-power amplifier. In additional in-line fiber coupled band pass filters were placed between amplification cascades to avoid arising of amplified spontaneous emission.

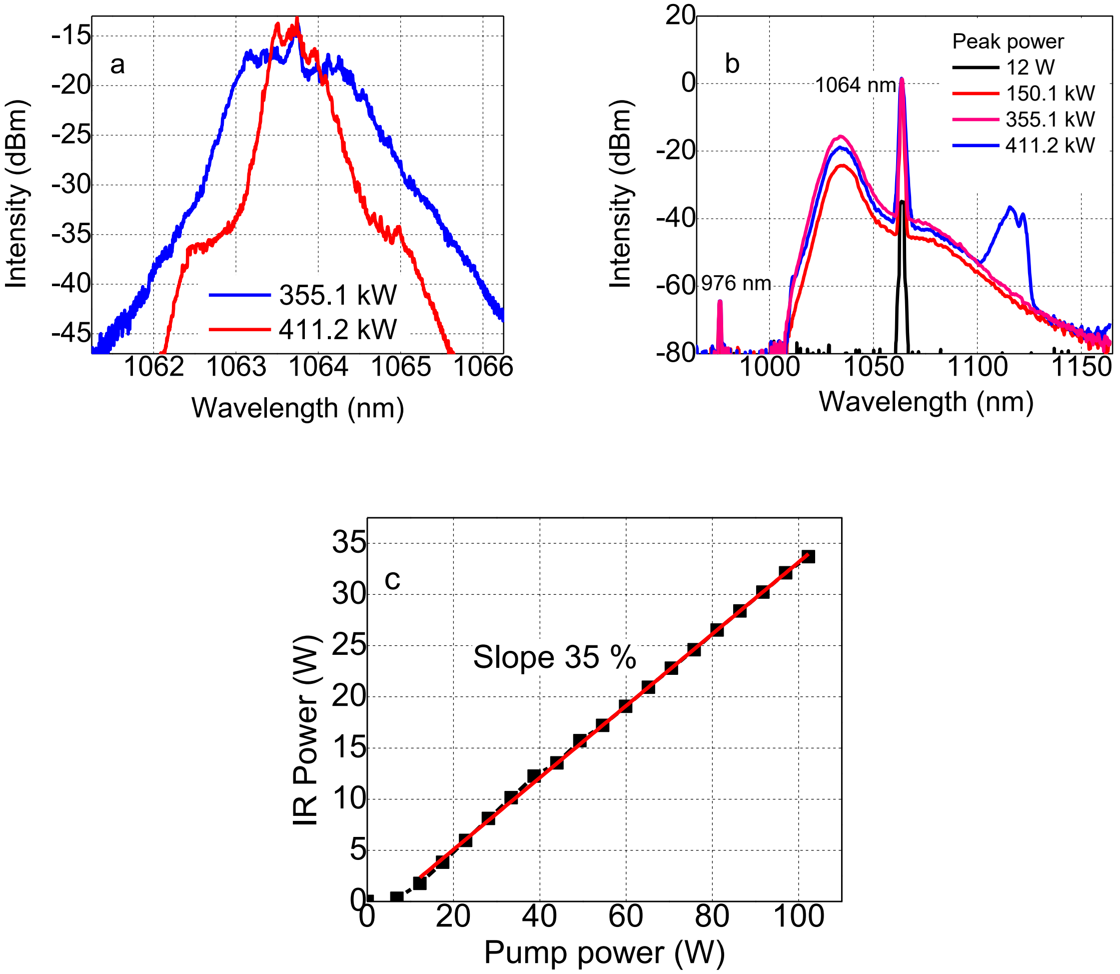

Fig. 3. (a) Spectra at the output of a high-power MOPA for 2.5 mW (red line) and 5 mW (blue line) of input signal; (b) Spectra at the output of a high-power MOPA for different peak powers of output pulses. Blue line corresponds to 5 mW of average input signal power, purple one corresponds to 2.5 mW of input signal; (c) Slope efficiency of high-power amplifier cascade.

The double-clad polarization-maintaining tapered Yb^{3+}-doped fiber (APM-T-DCF) was used as a gain medium for high-power amplification cascade [8]. APM-T-DCF had 4 m length and tapering ratio of about 3.3. The input part of the tapered fiber had core/cladding diameter equaled to 12.5/125 µm, while a wide part of the taper was 41/410 µm, corresponding to the constant core-to-cladding ratio of 10. The cross-section of the tapered fiber was PANDA type to maintain the state of linear polarized light. APM-T-DCF was optically pumped at 976 nm from the wide end of the tapered fiber through a free space unit using 100 W pump diode with multimode 105/125 µm fiber output. Free space unit was formed by two lenses collimating and focusing pump radiation respectively and dichroic mirror placed between lenses to separate pump and signal radiation. Dichroic mirror had a highly reflective coatings at 1064 nm and anti-reflective coatings at 976 nm.

The MOPA architecture based on the active tapered amplifier enabled to boost effectively the average power of narrowband picosecond IR radiation with relatively small spectral broadening for the repetition rates from 100 kHz to 80 MHz. Spectra of infrared radiation at different output powers at 1 MHz repetition rates is depicted in Fig. 3 (a,b). Spectral FWHM at a maximum pump power of high-power tapered amplifier was achieved less than 1 nm. Wherewith spectral bandwidth was directly depending on signal power and vary from 0.6 to 1 nm with increasing of signal power from 2.5 mW to 5 mW. Also increasing of signal power leads to arising of Raman scattering, that can be observed in Fig. 3 (b) blue line. Overall slope efficiency of high-power amplifier cascade reached 35 % at 1 MHz repetition rate. Relatively small value of slope efficiency is a consequence of low repetition rate and short pulse duration.

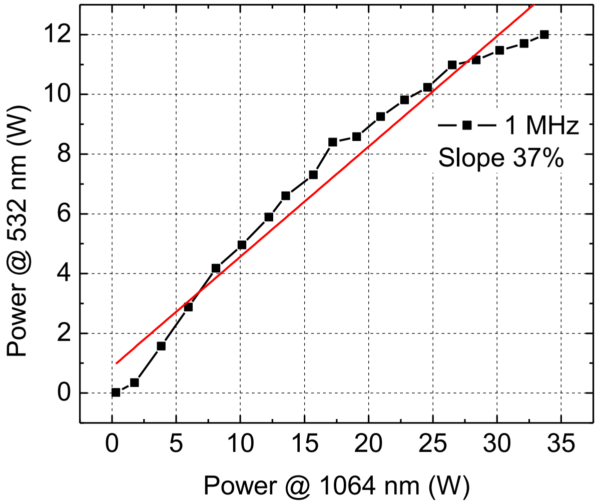

Fig.4. Output average power at 532 nm versus infrared power at 1064 nm.

Thereby, 33 W of average power at 1064 nm was achieved for picosecond pulses with 1 MHz repetition rate. The use of APM-T-DCF made it possible to amplify the signal with sufficiently high efficiency, while nonlinear effects such as Raman scattering had insignificant influence. In this case, the PANDA-structure of tapered fiber allows one to preserve the linear polarization state, and an irregular longitudinal geometric profile makes it possible to amplify a narrow-band signal with less spectral broadening in comparison with standard double-clad fibers with regular longitudinal profile.

After amplification, the generation of the second harmonic (SHG) was performed by an LBO crystal used a single-pass scheme. It provided up to 12 W of the average power for the green light with 37 % efficiency (Fig. 4). This corresponded to 12 μJ of the pulse energy and 146.4 kW of the maximum achieved peak power. The spectral linewidth was equaled to 290 pm at the central wavelength of 532 nm (measured with spectrum analyzer resolution of 0.05 nm). All main parameters including spectral FWHM, pulse energy and peak power of output radiation at 532 nm for different repetition rates are shown in Table 1. Maximum of peak powers were limited by achievable pump source power of 976 nm diode and also arising lasing at lower repetition rates. Table 1 also contains several sets of values at a frequency of 1 MHz as the most convenient repetition frequency for fast spectroscopic analysis, some applications of which require different narrowness of spectral bandwidth.

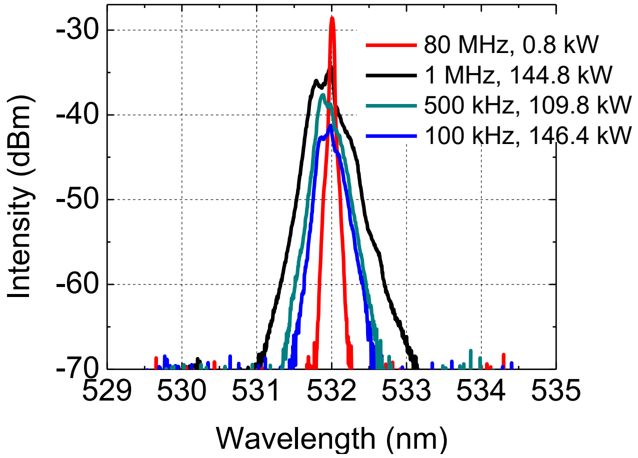

Fig. 5. (a) Green laser spectra at different repetition rate at maximum achieved peak power.

Table 1. Parameters of laser system output at 532 nm.

Repetition rate, Mhz	**Average power, W**	**Peak power, kW**	**Pulse energy, µJ**	**FWHM, pm**
80	5.4	0.82	0.07	51
1	12	146.4	12	289
	8.6	104.9	8.6	184
	2.4	29.3	2.4	118
0.5	4.8	117.1	9.6	219
0.1	1.2	146.4	12	237

3. CONCLUSIONS

The obtained results show the obvious advantages of the tapered based laser system. The gradual increase in the fiber core diameter in the direction of the amplified signal's propagation allows us to keep the effect of nonlinear effects at a low level and more effectively explore the stored energy of the active medium, unlike standard amplifiers based on cylindrical fixed-core fibers. The demonstrated green laser is promising for a wide range of time-resolved Raman spectroscopy applications that required single mode linear polarized output with short pulse duration and high pulse energy. The maximum average power at 532 nm was achieved equal to 12 W at 1 MHz repetition rate that corresponds to 12 µJ pulse energy and 146.4 kW of peak power with spectral bandwidth less than 290 pm. Moreover, original MOPA architecture allow to vary repetition rate in a wide range of frequencies from 100 kHz to 80 MHz with preservation of suitable parameters for different applications. However, the green laser scheme exhibits considerable flexibility which makes it applicable in various fields of science and technology.

REFERENCES

[1] Lipiäinen, T., Pessi, J., Movahedi, P., Koivistoinen J., Kurki, L., Tenhunen M. and Strachan, C. J., “Time-Gated Raman Spectroscopy for Quantitative Determination of Solid-State Forms of Fluorescent Pharmaceuticals,” Analytical Chemistry, 90(7), 4832–4839 (2018).

[2] Buckley, K. and Ryder, A. G., “Applications of Raman spectroscopy in biopharmaceutical manufacturing: a short review,” Appl. Spectrosc. 71, 1085–1116 (2017).

[3] Bersani, D. and Lottici, P. P., “Raman spectroscopy of minerals and mineral pigments in archaeometry,” J. Raman Spectrosc. 47, 499–530 (2016).

[4] Rull F., Maurice S., Hutchinson I., Moral A., Perez C., and Diaz, C., and The RLS Team, “The Raman laser spectrometer for the ExoMars rover mission to Mars,” Astrobiology 17, 627–654 (2017).

[5] Chen, K. K., Alam, S., Hayes, J., Lin, D., Malinowski, A. and Richardson, D. J., “100W, single mode, single polarization, picosecond, ytterbium doped fibre MOPA frequency doubled to 530nm” 2009 CLEO Pacific Rim, 2009. (2009).

[6] Dupriez, P., Sahu, J. K., Malinowski, A., Jeong, Y., Richardson, D. J. and Nilsson, J., “80 W green laser based on a frequency-doubled picosecond, single-mode, linearly-polarized fiber laser,” in Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies, Technical Digest (CD), paper CThJ1 (2006).

[7] Zhao, Z., Sheehy, B. and Minty, M., "180 W picosecond green laser from a frequency-doubled rod fiber amplifier," in Laser Congress 2018 (ASSL), OSA Technical Digest, paper AW1A.1 (2018).

[8] Fedotov, A., Noronen, T., Gumenyuk, R., Ustimchik, V., Chamorovskii, Y., Golant, K., Odnoblyudov, M., Rissanen, J., Niemi, T. and Filippov, V., "Ultra-large core birefringent Yb-doped tapered double clad fiber for high power amplifiers," Opt. Express 26, 6581-6592 (2018).