Diode-pumped lasers with intracavity Raman conversion

V. A. Orlovich[1], **P. A. Apanasevich**[1], **A. S. Grabtchikov**[1], **V. A. Lisinetskii**[1],
A. A. Demidovich[1], **I. A. Khodasevich**[1], **A. N. Kuzmin**[2], **and A. V. Kachynski**[2]

[1]*B.I.Stepanov Institute of Physics, National Academy of Sciences of Belarus;*
68 F.Skaryna Ave., 220072 Minsk, Republic of Belarus
[2]*The Institute for Lasers, Photonics and Biophotonics, Univ. at Buffalo; 458 NSC Buffalo, NY, USA 14260-3000*

The result of experimental investigation of continuous-wave (CW) diode-pumped microchip and mini lasers with an intracavity Raman conversion in a set of crystals is presented. Self-frequency Raman conversion effect in Nd:KGW, Yb:KYW, Nd:YVO$_4$, and Nd:BaWO$_4$ media in these lasers has been demonstrated for the first time to our best knowledge. Diode pumped microchip lasers with intracavity Raman conversion were proposed and realized in several nitrate, tungstate, and vanadate crystals. CW Raman generation in the mini lasers pumped by an Ar laser and a diode laser was demonstrated. Laser systems based on the Raman conversion and operating at fixed wavelengths as well as in the tunable spectral range of 188–1800 nm were designed.

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In recent decade, continuous-wave (CW) diode-pumped microchip and mini lasers have been extensively utilized in various applications. These devices are simple, compact, low-cost and highly efficient[1], and have a large marketing potential due to the feasibility of many technological and scientific applications[1,2]. A CW diode-pumped microchip and mini laser with passive or active Q-switching can generate pulses of duration in the range of 0.3–20 ns and of peak power up to dozens of kilowatts[3]. This allowed high-efficiency nonlinear laser wavelength conversion to the harmonics (second, third, fourth, and fifth) and resulted in a new generation of compact lasers operating at a certain visible and ultraviolet wavelengths with the subsequent application in ranging, imaging, micromarking, material processing, laser-induced fluorescence/breakdown spectroscopy, and other applications. The use of CW diode-pumped microchip and mini lasers with optical parametric oscillators allowed to design advanced laser sources with tunability of emission wavelength[4].

Stimulated Raman scattering (SRS) has been employed for more than 40 years as a method for frequency conversion of laser radiation to reach new spectral ranges. Raman conversion has been successfully applied to pulsed nano- and femtosecond laser systems with the pulse power of hundreds of kilowatts[5]. This level of power is needed mainly to exceed conversion threshold for typical Raman media. Usually diode-pumped pulsed lasers with pump power less than 4 W (low power) produce output peak power in the range of several tens of kilowatts[3]. Therefore, to achieve SRS frequency conversion for low power diode-pumped (and other types) lasers, Raman threshold should be decreased noticeably. To design low power diode-pumped solid-state lasers with Raman conversion we used: 1) the crystals of nitrates, tungstates, and vanadates, i.e., Raman media with high Raman gain coefficient; 2) a high-finesse of Raman cavity design; 3) an intracavity Raman conversion, when Raman media is placed into a cavity of diode-pumped microchip and mini laser. This approach allowed us to observe pulsed self-frequency Raman conversion in low power diode-pumped solid-state lasers[6], and to use intracavity Raman conversion effect for generation of the Stokes pulses with duration down to 50 ps and peak power up to 40 kW[7] on the base of a simple and compact design of passively Q-switched microchip and mini- lasers. We also demonstrated CW Raman generation in diode-pumped mini lasers[8,9] and pulsed solid-state laser systems based on the Raman conversion and operating at fixed wavelengths as well as tunable in the spectral range of 188–1800 nm[10].

A large number of laser crystals is also known as efficient Raman media. In lasers based on these crystals so-called effect of self-frequency Raman conversion (SFRC), when laser operation and Raman conversion take place simultaneously in the same crystal, can be observed. Robust and simple design of SFRC lasers makes them attractive for different applications. We have found the SFRC effect in CW diode-pumped passively Q-switched mini- and microchip lasers based on Nd:KGW, Yb:KYW, Nd:YVO$_4$, and Nd:BaWO$_4$ for the first time to our best knowledge[5,6]. The laser diodes with output power up to 1 W were used as a pump source for SFRC. The laser cavity design was the following. An input mirror has a high reflectance ($R \approx 99.95\%$) at laser and first Stokes wavelengths, while an output mirror possesses a high reflectance at laser ($R \approx 98\%$) and optimal reflectance at first Stokes wavelengths. Typically the threshold of Stokes emission was about 200–400 mW of laser diode pump power. In dependence on type of laser and

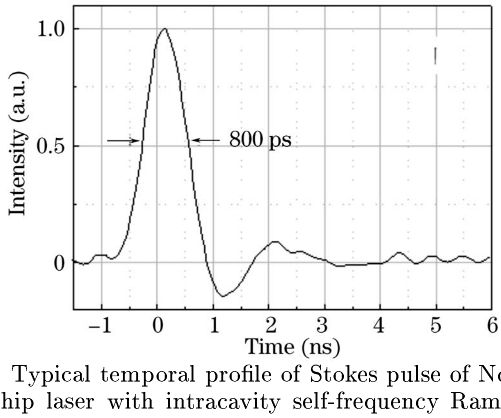

Fig. 1. Typical temporal profile of Stokes pulse of Nd:YVO$_4$ microchip laser with intracavity self-frequency Raman conversion.

cavity design the Stokes pulses with duration from 800 ps (Fig. 1) up to tens of nanoseconds and repetition rate in the range of 8–50 kHz were observed. The maximum efficiency of laser diode power conversion to the Stokes power was about 3%. Our numerical calculations show the possibility of Raman pulse shortening up to 100 ps and increasing the conversion efficiency through the optimization Raman laser cavity.

One of the ways of increasing the efficiency of Raman conversion and shortening the pulse width of Raman component, as investigations described above show, is the employing the lasers with short cavity (mini- and microchip lasers) for intracavity Raman conversion. In this case the efficient laser and Raman media are used as separate crystals to combine the features of high laser amplification and high Raman gain simultaneously. To fulfill these experiments we used different combinations of Nd:LSB and Nd:YAG microchip lasers and $Ba(NO_3)_2$, $BaWO_4$, $PbWO_4$, YVO_4 and diamond Raman media[7]. We realized the intracavity Raman compression conditions, when the Stokes pulses (Fig. 2) were much shorter (48 ps) and much powerful (40 kW) than that for optimized Nd:LSB laser without intracavity Raman element (800 ps and 3 kW, respectively). We also investigated the nonlinear conversion — harmonics and sum frequency generation — of laser output and the first Stokes component in Nd:LSB/$Ba(NO_3)_2$ microchip laser with an intracavity Raman conversion. Efficiency of second harmonic generation up to 50% was reached. During our investigation we observed the emission of eleven lines in the spectral range of 239–1196 nm with the power high enough to be used in spectroscopy, luminescence excitation, and medicine.

Earlier due to high SRS excitation threshold the Raman conversion of CW lasers has been obtained only for limited number of special cases: 1) resonant Raman scattering in gases; 2) SRS in optical fibers; and 3) oscillation in a hydrogen Raman laser with a high-finesse cavity ($F > 10000$). We performed theoretical calculations and then demonstrated experimentally a CW Raman generation of output power up to 100 mW in the crystal media with high Raman gain coefficient placed into Raman cavity with relatively low magnitude of finesse ($F \approx 1000$). Three types of CW Raman laser design were evaluated. In the first case the generation was obtained in a single resonant cavity with $Ba(NO_3)_2$ crystal as a Raman media[8]. The Raman laser is pumped by multimode radiation of commercially available argon-ion laser (514 nm). Raman oscillation threshold is reached at 2 W of pump power. The maximum output Stokes power was measured to be 164 mW with the conversion efficiency to Stokes output of 6%. In the second case a CW Raman generation in a compact solid-state laser system pumped by a multimode diode laser was demonstrated[9]. The Stokes radiation at 1181 nm was observed as a result of SFRC the 1067-nm laser radiation in Nd:KGW crystal. Raman threshold was measured to be at the level of 1 W of laser diode pump power. The highest output power obtained at the Stokes wavelength was more than 80 mW. Third design was based on Nd:YVO_4 mini laser with the $Ba(NO_3)_2$ (or $PbWO_4$) Raman crystal inside the cavity. CW Raman threshold in the third case was estimated to be about 0.5 W of laser diode pump power. At the pump power of 1 W the Stokes radiation output power exceeded 10 mW[9]. The results of these studies demonstrate the possibility to design simple, inexpensive and compact solid-state Raman lasers for frequency conversion of commercially available CW lasers operating in the different spectral ranges.

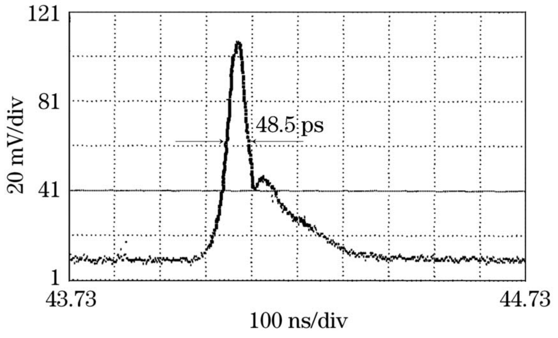

Fig. 2. Typical temporal profile of Stokes pulse of Nd:LSB microchip laser with intracavity Raman conversion in $Ba(NO_3)_2$ crystal.

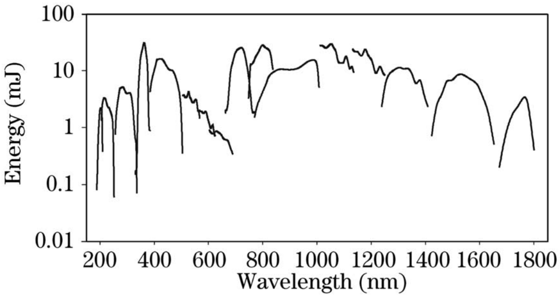

Fig. 3. Tuning curves of solid-state pulsed laser system, based on the complex application of the tunable LiF:F_2^- and MOPA-Ti:Sa lasers, harmonic generators and Raman lasers.

In many applications (spectroscopy, photophysics, photochemistry, life sciences, environment control, etc.) pulsed lasers emitting tunable radiation are widely used. We have developed solid-state laser system based on the complex application of the tunable lasers, harmonics generators and Raman lasers[10]. The system is based on the following laser devices: a commercial LiF:F_2^- laser (tuning range 1090–1240 nm), a specially developed single-mode master oscillator power amplifier Ti:sapphire (MOPA-Ti:Sa) laser (tuning range 662–1008 nm), generators for the second, third, and fourth harmonics and a Raman laser using a barium nitrate crystal which is pumped by the LiF:F_2^- laser radiation or radiation of its second harmonic or radiation of the MOPA-Ti:Sa laser. For pumping the LiF:F_2^- laser and the MOPA-Ti:Sa laser, the radiation from a commercially available nanosecond 10-Hz Nd:YAG laser with pulse energies of about 500 and 300 mJ at fundamental frequency and at its second harmonic, respectively, is used. This laser system produced narrowband (< 1 cm^{-1}), continuously tunable radiation on the range 188–1800 nm with pulse energies of 0.1–80 mJ (Fig. 3).

In conclusion, we have demonstrated that SRS in the crystal media is a simple and an efficient method of frequency conversion of a pulsed as well as CW emission of diode-pumped solid-state lasers.

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