Continuous-wave Raman generation in a diode-pumped Nd\textsuperscript{3+}:KGD(WO\textsubscript{4})\textsubscript{2} laser

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Continuous-wave Raman generation in a compact solid-state laser system pumped by a multimode diode laser is demonstrated. The Stokes radiation of stimulated Raman scattering at 1.181 \( \mu \text{m} \) is generated as a result of self-frequency conversion of the 1.067 \( \mu \text{m} \) laser radiation in Nd\textsuperscript{3+}:KGD(WO\textsubscript{4})\textsubscript{2} crystal placed in the cavity. The Raman threshold was measured at 1.15 W of laser diode power. The highest output power obtained at the Stokes wavelength was 54 mW. The anomalous delay of Raman generation relative to the start of laser generation (the oscillation buildup) due to slow accumulation of Stokes photons in the cavity at low Raman gain and Raman threshold dependence not only on the laser intensity but also on the time of laser action are observed. © 2005 Optical Society of America

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Pulsed and continuous-wave (cw) operating diode-pumped solid-state lasers (DPSSLs) are attractive due to such advantages as compactness, robustness, efficiency, and easy maintenance. Stimulated Raman scattering (SRS) is a method to use for frequency conversion of laser radiation in such lasers. Raman conversion in solid-state mediums (crystals) was successfully employed in the pulsed regime.\textsuperscript{1,2} This approach allows demonstration of compact passive and active Q-switched DPSSLs with Raman conversion.\textsuperscript{3–5} Recently the pulsed Raman conversion has been realized in DPSSLs with different solid-state media for frequency shifting the tunable radiation\textsuperscript{6} and also in a microchip laser.\textsuperscript{7} The possibility of generating pulses of up to 50 ps duration at Raman compression in a microchip laser has been also shown.\textsuperscript{8}

Realization of Raman conversion of cw radiation is usually treated as a serious problem owing to high (more than 100 kW) pump powers needed for SRS to occur. Some years ago it was shown that the Raman threshold can be essentially reduced in a high-finesse Raman laser pumped with monochromatic radiation.\textsuperscript{9} This Raman laser pumped with a cw single-frequency diode laser allows a 240 \( \mu \text{m} \) threshold and a 70% photon-conversion efficiency to be achieved.\textsuperscript{10} So impressively low Raman threshold and high conversion efficiency were obtained because of the perfectly matched parameters of the pump radiation and the high-finesse cavity of the Raman laser that was feasible at pumping with monochromatic radiation.

It is impossible to achieve such good matching with multimode radiation pumping. Nevertheless, cw generation has been recently obtained in a Raman laser with multimode pumping.\textsuperscript{11} This was possible because of the employment of a solid-state Raman medium with a high Raman gain coefficient (barium nitrate crystal) in the cavity when pumped with the high spatial quality beam of an Ar laser. The increased Raman threshold of nearly 2 W in this experiment is still acceptable for frequency conversion in many lasers delivering 1–10 W of output. Powers of 10 W or more can be obtained from multimode diode lasers. But the direct use of such diode lasers to pump Raman lasers is limited because of the spatial and spectral properties of their radiation. This problem, however, can be avoided by use of intracavity Raman generation in DPSSLs. Up to now, Raman generation in DPSSLs was limited, to our knowledge, to the pulsed regime.

In this Letter we present the first results on cw intracavity Raman generation in a compact solid-state laser system pumped with multimode radiation from a diode laser. The intracavity approach allows the laser power, obtained at high-efficiency generation with diode pumping, to be concentrated in the cavity for further efficient excitation of SRS in this cavity.

A neodymium-doped potassium gadolinium tungstate \([\text{Nd}^{3+}:\text{KGD(WO}_4)_2]\), \((\text{Nd}:\text{KGW})\) crystal was chosen for a Raman medium. The crystal can simultaneously support both laser and Raman generation. Such Raman conversion is usually termed Raman self-conversion. The combination of laser and Raman processes in one element allows for reduction of the number of cavity optical surfaces, resulting in a decrease of intracavity losses. This property is very important for cw Raman conversion in the intracavity...
scheme, as cw Raman generation is strongly sensitive to intracavity losses.\textsuperscript{11} In addition, it also provides easy and optimal matching between the laser and Stokes modes.

Nd:KGW is known as an efficient Nd\textsuperscript{3+}-containing laser medium. In comparison with conventionally used Nd:YAG crystals, the main features of anisotropic Nd:KGW are a large emission cross section and a wide absorption spectrum. The 1.067 \( \mu \text{m} \) Nd:KGW laser radiation is polarized, which is important for subsequent polarization-sensitive nonlinear conversion. Besides, the KGW host has a high third-order nonlinear susceptibility. Therefore this crystal is one of the most promising Raman-active media.

There are several lines of spontaneous Raman scattering whose emergence depends on the orientation of the pump beam and polarization toward the crystal indicatrix axes.\textsuperscript{12} The most intensive Stokes lines have frequency shifts of 767.5 and 901.5 cm\textsuperscript{-1}. The Raman gain coefficient for both lines is 3.5 cm/GW.\textsuperscript{13}

Figure 1 shows the setup for cw Stokes generation in the Nd:KGW laser with intracavity self-Raman conversion. A laser diode (2.4 W at 0.8075 \( \mu \text{m} \), Model ML151 from Milon Laser) coupled to a 100 \( \mu \text{m} \) optical fiber was used as a pump source. Two coupling lenses inserted in front of the optical fiber provided the Gaussian profile of the pump beam waist with a diameter of 150 \( \mu \text{m} \) (\( M^2 = 39 \)). A 40 mm long Nd:KGW crystal with a Nd concentration of 3 at. \% (cut along the \( b \) crystallographic axis) was used. The input mirror was deposited directly on the facet of the laser crystal. It had a transmission of 95\% at the laser diode wavelength and reflection of \( R = 99.9\% \) and \( R = 99.6\% \) at 1.067 and 1.181 \( \mu \text{m} \), respectively. The other facet of the laser crystal had antireflection coating (reflection \( R < 0.1\% \)) at 1.067 and 1.181 \( \mu \text{m} \). A mirror with a curvature radius of 50 mm and with reflection of \( R = 99.96\% \) at the 1.067 \( \mu \text{m} \) wavelength and \( R = 99.97\% \) at the 1.181 \( \mu \text{m} \) wavelength was used as an output coupler. The geometrical length of the cavity was \( \sim 50 \text{ mm} \). The pulsed operation of the diode laser (pulse duration 10 ms, repetition rate 20 Hz) allowed the start and evolution of the laser and Stokes generation to be observed. Evidence of Raman conversion was a spectral observation of a Stokes line (1.181 \( \mu \text{m} \) ) shift by 901 cm\textsuperscript{-1} relative to the laser line, in agreement with the value of the Raman shift in KGW. The output power characteristics of the Raman laser are shown in Fig. 2.

The laser generation threshold in Nd:KGW was reached at 55 mW of diode power. The Raman threshold was obtained at 1.15 W of diode power. The output Stokes power measured at the output mirror did not exceed 8.9 mW, but the Stokes power leaking through both of the cavity mirrors was 54 mW at the diode power of 2.06 W, corresponding to an efficiency of 2.6\%. Under these conditions the intracavity Stokes power was estimated as 60 W and the intensity as 200 kW/cm\textsuperscript{2}. The corresponding laser power in the cavity was 130 W, and the intensity was 440 kW/cm\textsuperscript{2}. The output Stokes beam quality factor \( M^2 \) did not exceed 1.2.

The temporal behavior of the laser and Stokes generation is shown in Fig. 3. The laser generation starts as relaxation oscillations with continuous transition to the steady-state level. These oscillations continue for \( \sim 40 \text{ ms} \) for the low pump level (Fig. 3A). An increase in the pump power leads to shortening of the transition period with oscillations and to the appearance of a Stokes signal (Fig. 3B). The Stokes signal is strongly delayed relative to the start of laser generation in spite of the fact that the laser intensity is stabilized at the threshold level long before the Stokes
signal is observed. Further growth of the pump power results in a decreased delay interval (Fig. 3C).

The measured dependence of the time delay of Raman generation on laser power is shown in Fig. 4. The delay is approximately inversely proportional to the laser power and changes from 80 to 15 μm for the maximum laser level in the experiment. The maximal delay of Raman generation observed in the experiment was ~300 μm. Such temporal development of Stokes radiation is in contrast with traditional nanosecond-pump pulsed Stokes generation experiments, especially in the single-pass scheme, where the pump intensity determines the Raman threshold and the delay of the Stokes generation is usually not taken into account (it is in the subnanosecond interval).

This result can be understood from analysis of the steady-state equation for Stokes power. Assuming a linear regime without pump depletion, the equation can be written as

$$\frac{dP_S}{dt} = \frac{c}{L_C} (P_P G_S P_S - L_S P_S),$$  

where $P_S, P_P$ are the Stokes and laser powers inside the cavity, respectively; $L_C$ is the cavity length; $L_S$ is the single-pass losses; and $G_S$ is the single-pass gain per unit pump power. The solution is

$$P_S(t) = P_{S0} \exp \left\{ \int_0^t \left[ P_P(t') G_S - L_S \right] \frac{c}{L_C} dt' \right\},$$

where $P_{S0}$ is the Stokes seed power. The expression in the exponent equals 25 near the Raman threshold. After transformation, the point of time at which the Raman threshold is reached, can be presented as

$$T_B = \frac{25L_C}{c(G_S P_P - L_S)}.$$  

The delay of Raman signal $T_B$ is inversely proportional to the laser power, which is in accordance with the experimental data (see Fig. 4). For laser powers closer to the Raman threshold, where gain is small, more time for accumulation of Stokes photons in the cavity is needed for stimulated Raman scattering to occur. The expression for $T_B$ shows that the Raman threshold is defined by both the laser power and the temporal interval in which the laser acts. This phenomenon was previously discussed only theoretically for Raman lasers.

The effect of the delay in laser generation with respect to the pump start is well known for ordinary lasers with inversion as an oscillation buildup. This buildup corresponds to the time evolution of the generated field from the noise level to the steady-state level with a large number of photons accumulated in the cavity. Observation of this effect in our experiments demonstrates the importance of photon accumulation also in the cavity of a cw Raman laser.

In conclusion, we have demonstrated what we believe to be the first all-solid-state laser system with cw Raman generation. Raman generation was obtained as intracavity self-frequency conversion in a Nd:KGW laser pumped with a 2 W multimode diode laser. We observed an oscillation buildup in the Raman laser and dependence of the Raman threshold on both the laser intensity and duration of the laser action.

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References


![Fig. 4. Effect of laser power on the Raman generation delay. Dots, experimental data; curve, result of approximation by the expression for $T_B$.](image-url)