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Rapid communication

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Nd:KGW/KGW crystal: efficient medium for continuous-wave intracavity Raman generation

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ABSTRACT Diode pumped continuous-wave intracavity Raman conversion in a composite Nd:KGW/KGW crystal has been investigated. The use of a Nd:KGW/KGW crystal instead of the ordinary Nd:KGW crystal has made it possible to considerably decrease intracavity losses. A Raman threshold corresponding to a diode laser power of 230 mW and a quantum efficiency of conversion of diode laser radiation to the Stokes radiation of 22% have been obtained.

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1 Introduction

In the last several years, Raman conversion has gained recognition as a method of continuous-wave (cw) laser frequency conversion [1–3]. Investigations of Raman conversion in crystals occupy a special place due to the attractiveness of the solid-state approach and diode pumping [4–6]. The lasing efficiency of such systems is of particular importance in terms of their future applications. Since the Raman gain is relatively small, the lasing efficiency of cw Raman lasers strongly depends on the losses and, accordingly, on the laser schemes used.

There are two schemes of diode-pumped solid-state laser systems with Raman conversion. In the first scheme (intracavity Raman conversion) the laser and Raman media are located in the laser cavity [4, 5, 7]. The laser radiation generated in the laser active medium is then converted to Stokes radiation in the Raman medium. In the second scheme (intracavity self-frequency Raman conversion), the laser active medium is simultaneously the Raman medium [4, 8, 9]. In one medium both generation of laser radiation and its Raman conversion, take place. For cw Raman conversion the second scheme looks more attractive than the first one because of the smaller intracavity surface losses. However, recent experiments have shown that the intracavity Raman conversion in a $PbWO_4$ crystal placed in the $Nd:YVO_4$ laser cavity [7] has a much lower threshold and a higher efficiency than the intracavity self-frequency Raman conversion in a Nd:KGW ($Nd:KGd(WO_4)_2$) crystal [8], or a $Nd:YVO_4$ crystal [9]. This fact can be explained by the higher level of losses in the crystals with intracavity self-frequency conversion. One of the dominant causes responsible for these losses can be the two-photon absorption by Nd ions resulting from the ${}^4I_{9/2} \to ({}^2G, {}^4G)_{7/2}$ and ${}^4I_{9/2} \to {}^4G_{5/2} + ({}^2G, {}^4G)_{7/2}$ transitions [10].

Laser generation in Nd:KGW arises from luminescence of the Nd ions contained in the crystal. Because of the short confocal parameter of the diode pump beam (a few millimeters) and the strong absorption of the pump radiation, the interaction region occupies the short part of the active crystal. Therefore, short-length, highly doped active crystals can be used for laser generation.

On the other hand, the confocal parameter of the generated laser radiation in the cavity is usually relatively long (a few centimeters). Therefore, to optimize the Raman amplification a long crystal is needed. Hence, long Nd-doped active crystals were used for cw intracavity self-frequency Raman conversion [4–9]. However the presence of Nd-ions in active crystals leads to additional losses at the laser and Stokes wavelengths along the full length of the crystal.

It may be concluded that for efficient intracavity self-frequency Raman conversion, the following conditions should be met: the active crystal should be long enough to provide a high Raman gain and the Nd ions should be contained only in the small part of this crystal. These conditions are fulfilled in a composite crystal, where the small (a few millimeters long) part of the Raman active crystal is doped with Nd ions, and the remaining (a few centimeters long) part is undoped. Such crystals are already used in laser generation to improve the cooling conditions [11].

The investigation of the diode -pumped laser with cw intracavity self-frequency Raman conversion based on a composite KGW (Nd:KGW/KGW) crystal is a topic of present paper.

2 Experiment

Figure 1 shows the experimental setup. As a pump source a fiber-coupled (100 μm) laser diode (2.4 W at 0.808 μm, Model ML151 from Milon Laser) connected to the laser driver (Model LDD-10 from ATC SD) was

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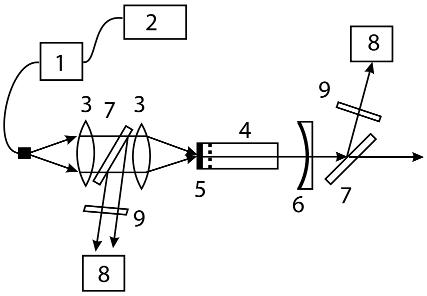

FIGURE 1 Experimental setup. 1 – diode laser; 2 – driver; 3 – lenses; 4 – active element; 5 – input mirror; 6 – output coupler; 7 – beam splitters; 8 – power meters, spectrometer, oscilloscope; 9 – interference filters

used. The beam emerging from the fiber was imaged onto the laser crystal by a coupling two-lens system installed in front of the optical fiber, providing a nearly Gaussian intensity profile with a diameter of 100 μm ($M^2 = 42$).

As an active medium, a 50 mm long Nd:KGW/KGW crystal was used. It was manufactured at Vavilov State Optical Institute. This crystal was cut along the b axis. A 5 mm long part of the crystal was doped with Nd-ions with a concentration of 4 at. %, and the remaining part was undoped. The crystal was mounted on a copper heat sink with the aid of a heat-conducting paste.

As in [8], the laser cavity was formed by two mirrors highly reflective at the fundamental and Stokes frequencies. The geometrical cavity length was equal to 55 mm. The input mirror was evaporated on the input face of the Nd:KGW/KGW crystal. This mirror transmitted 98% of the pump radiation and reflected about 99.9% at the laser (1.067 μm) and Stokes (1.181 μm) wavelengths. The output face of the Nd:KGW/KGW crystal had an antireflection coating. The residual reflectance of this coating was less than 0.1%. The output spherical mirror had a curvature radius of 46 mm. It reflected 99.95% and 99.8% at the laser and Stokes wavelengths, respectively.

To separate the laser and the Stokes radiation, interference filters were used. To measure the output power at the fundamental and Stokes wavelengths at both sides of the laser cavity, the beam splitters were employed.

Measurements of output spectra were made with a spectrometer connected to a CCD array. The oscilloscope traces of output radiation were registered by a photodiodes and a Tektronix TDS 5104 digital oscilloscope.

3 Results and discussion

The laser generation threshold at the fundamental wavelength was reached at a laser diode power of 18 mW, and for the Stokes generation threshold the laser diode power was 230 mW. These thresholds are several times lower than those obtained in previous work [8] for a similar laser with intracavity self-frequency Raman conversion in a doped 40 mm long Nd:KGW crystal (the laser and Raman thresholds corresponded to laser diode powers of 55 mW and 1.15 W, respectively). The low thresholds obtained in a laser with the composite KGW crystal are indicative of the low intracavity losses.

Low losses lead also to a change in the oscilloscope traces for the generation evolution. Figure 2 shows the generation evolution for the radiation at the fundamental and Stokes wavelengths. It is seen that the delay of the Stokes generation relative to the laser generation is very short. The Stokes radiation arises on relaxation oscillations of the laser radiation. This behavior differs widely from the evolution observed in other cw lasers with both intracavity self-frequency Raman conversion and intracavity Raman generation, where a long delay time (tens of microseconds) for Stokes generation was observed [7–9]. The Stokes radiation delay time (T_B) can be given as [8]:

$$T_B = 25\frac{L_C}{c}\frac{1}{G_S P_P - L_S}\,, \qquad (1)$$

where P_P is the intracavity power at the laser wavelength, L_C is the optical length of laser cavity, c is the velocity of light, G_S is the single pass gain of the Stokes radiation per unit pump power, and L_S denotes the single pass losses of the Stokes radiation.

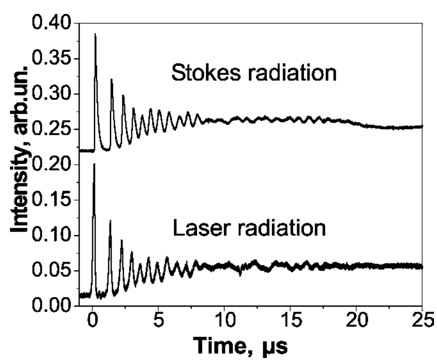

FIGURE 2 Oscilloscope traces for the laser and Stokes signals

Expression (1) shows that the small delay time can be explained by low single pass losses of the Stokes radiation (L_S) or high intracavity power at the fundamental wavelength (P_P). The intracavity power (P_P) depends in turn, on the fundamental wavelength losses. Low intracavity losses in the crystal at the laser and Stokes wavelengths lead to both a decrease in the single pass losses (L_S) and an increase in the intracavity power (P_P). Thus the small delay time also points to low losses in the composite KGW crystal.

We suppose that the decrease in the losses in the composite KGW crystal compared to the doped KGW crystal is due to the minimization of the two-photon absorption at both the fundamental and the Stokes wavelength caused by the $^4I_{9/2} \rightarrow (^2G, {}^4G)_{7/2}$ and $^4I_{9/2} \rightarrow {}^4G_{5/2} + (^2G, {}^4G)_{7/2}$ transitions, respectively [10]. The decrease in the losses also leads to an increase in the output power of the Stokes radiation and its generation efficiency.

The dependences of output powers at the fundamental and Stokes wavelengths on the laser diode power are shown in Fig. 3. The powers were measured in both directions from the laser cavity. A Stokes power of up to 277 mW was attained at a laser diode power of 2 W. This corresponds to an effi-

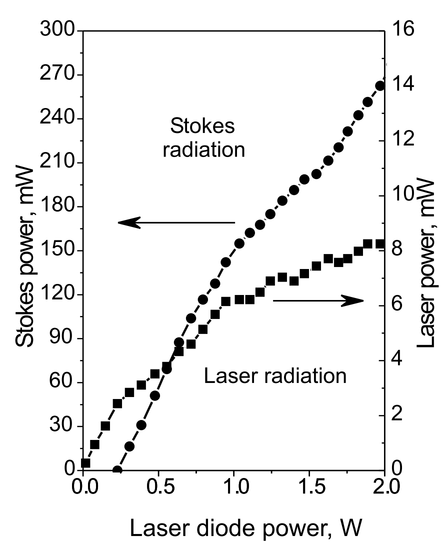

FIGURE 3 The dependencies of output powers at the fundamental and Stokes wavelengths on the absorbed laser diode power

ciency of conversion of laser diode to Stokes radiation power of about 14%. The efficiency of conversion of the number of laser diode radiation quanta into the number of Stokes radiation quanta (quantum efficiency) was 20%. To our knowledge, these are the highest efficiencies attained by now in diode-pumped lasers with cw Raman conversion. The Stokes beam had a smooth, almost Gaussian spatial intensity distribution with a beam quality factor M^2 of about 1.4.

Figure 3 shows that once the Raman threshold has been reached, the increase in the laser intensity becomes somewhat less rapid. This is explained by the considerable conversion of laser to Stokes power. Actually the laser power should only increase with increasing laser diode power until the Raman threshold is reached. When the Raman threshold is reached, the laser power in the cavity should be equal to that of the Raman threshold and should not increase any more [12]. The increase in the laser power observed in this and in the other experiments [4, 5, 7–9] is explained by the increase in the laser spectrum linewidth.

The radiation linewidths at the fundamental and Stokes wavelengths depended on the laser diode pump power. The dependencies are shown in the Fig. 4. An increase in both linewidths is seen. Thus, the fundamental radiation linewidth was equal to 5 cm^{-1} at the generation threshold and increased to 24 cm^{-1} at a high laser diode power. For the Stokes radiation, the linewidth was 1.6 cm^{-1} at the threshold and 11 cm^{-1} at a high pump power. This increase in the fundamental radiation linewidth explains the increase in the fundamental radiation power when the Raman threshold is reached (Fig. 3). At high pump power an additional laser line of the $^4F_{3/2} \rightarrow {}^4I_{11/12}$ transition with a wavelength of 1.075 μm was generated. This line did not take part in the Raman conversion and contributed to the increase in the laser power.

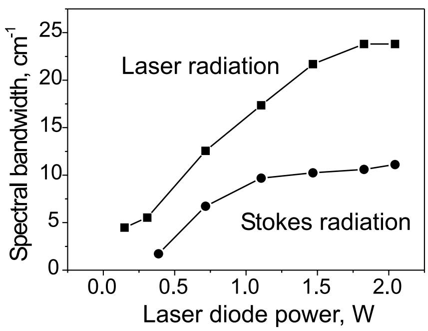

FIGURE 4 The dependencies of laser and Stokes radiation linewidths on the laser diode power

4 Conclusion

For the first time intracavity self-frequency Raman conversion in a composite Nd:KGW/KGW crystal has been demonstrated. The use of a composite crystal for cw Raman conversion has made it possible to lower the Raman threshold to a value corresponding to the laser diode power of 230 mW. An output Stokes power of 277 mW has been attained at a pump power of 2 W. A quantum efficiency of 20% for conversion of laser diode to output Stokes radiation has been obtained. This approach demonstrates one way of increasing the Raman conversion efficiency in continuous-wave laser systems.

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