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# Transverse mode locking of the Stokes component of a diode end-pumped $Q$-switched Nd:KGW laser

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***Abstract.*** **Lasing in a solid-state inhomogeneously diode end-pumped Nd:KGW/Cr$^{4+}$:YAG laser is obtained at wavelengths of 1067 and 1181 nm (Stokes shift 901 cm$^{-1}$) under conditions of frequency degeneracy of cavity modes. In this case, the radiation has a characteristic ring spatial structure, which testifies to transverse mode locking of the fundamental and Stokes components. The possibility of controlling the Raman conversion efficiency by changing the position of an undoped KGW crystal additionally installed in the cavity is demonstrated. It is shown that the transverse mode locking is accompanied by the total longitudinal mode locking at $\lambda$ = 1067 and 1181 nm.**

***Keywords:*** *solid-state lasers, longitudinal diode pumping, transverse mode locking, stimulated Raman scattering, SRS self-conversion.*

## 1. Introduction

Stimulated Raman scattering (SRS) is an effective and generally accepted method of generation of light at new wavelengths in lasers, including diode-pumped solid-state lasers (DPSSLs). The most popular SRS-active media for self-conversion in DPSSLs are $Nd^{3+}$-doped $KGd(WO_4)$, $BaWO_4$, $Ba(NO_3)_2$, and other crystals [1]. Lasing at Stokes frequencies in DPSSLs can be achieved as a result of intracavity SRS conversion in additional SRS crystals [2, 3] or due to SRS self-conversion [2]. The parameters of the Stokes component in DPSSLs with SRS conversion are to a large extent determined by the parameters of the fundamental laser radiation. It was demonstrated [4–7] that, in the case of inhomogeneous longitudinal pumping and a degenerate cavity, it is possible to obtain a transverse mode locking regime. For this purpose, one should use inhomogeneous pumping. The pump inhomogeneity is characterised by parameter $s = w_0/w_p$, i.e., by the ratio of the radius of the zero mode of the empty cavity $w_0$ to the pump beam radius $w_p$. Transverse mode locking is possible at $s > 1$, and the spatial radiation structure will be considerably different from Gaussian in the case of fulfilment of the condition

$$\frac{\arccos\sqrt{g_1 g_2}}{\pi} = \frac{r}{s},$$

where $r/s$ is the proper irreducible fraction, which characterises the degeneracy; $g_{1,2} = 1 - L/R_{1,2}$ are the cavity stability parameters; $R_{1,2}$ are the radii of curvature of cavity mirrors; and $L$ is the cavity length. In this case, the lasing threshold considerably decreases [4, 6], a specific non-Gaussian field structure is formed [5, 7], and radiation is concentrated in the region of inhomogeneous pumping in the active element (AE) [5]. At the same time, in the ranges of $L$ between the values corresponding to the frequency degeneracy of cavity modes, the laser radiation structure is close to the Gaussian mode structure. This behaviour was demonstrated for lasers operating in both cw and $Q$-switched regimes.

Interest in transverse mode locking in diode end-pumped solid-state lasers is related to the possibility of controlling the laser radiation parameters [8–13]. Transverse mode locking is also of interest for the development of diode end-pumped solid-state lasers with intracavity SRS conversion because it opens the possibility for decreasing the SRS lasing threshold and increasing the SRS efficiency. A noticeable decrease in the threshold and a concentration of radiation in the region of the AE pumping [5, 13–15], which are characteristic for transverse mode-locking, are advantageous for frequency self-conversion in Raman-active crystals.

The present work is devoted to the experimental study of intracavity SRS in Raman-active Nd:KGW crystal under conditions of transverse mode locking. The behaviour of the spatial and temporal structures of the fundamental and the Stokes radiation components in the case of $Q$-switching by a Cr$^{4+}$:YAG saturable absorber under inhomogeneous end-pumping is studied depending on the cavity configuration. The possibility of controlling the intracavity SRS efficiency by changing the position of the KGW crystal in the cavity under the conditions of transverse mode locking is considered.

## 2. Experimental setup

The laser scheme is shown in Fig. 1. The laser cavity was formed by two mirrors, M1 and M2. Spherical mirror M1 with a radius of 150 mm was highly reflecting ($R$ = 99.96%) for radiation with wavelengths of 1067 and 1181 nm and antireflection coated ($R$ < 1%) for a pump wavelength $\lambda_p$ = 811 nm. The reflection coefficients of plane mirror M2 were 99.96% and 96% for wavelengths of 1067 and 1181 nm, respectively. As an active medium, we used a Nd:KGW (2 at. %) crystal 12 mm long cut along the $N_p$ axis corresponding to the [010] crystallographic axis. The crystal was

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wrapped in indium foil and mounted in a copper heat sink near mirror M1. The AE faces were antireflection coated for lasing wavelength in the range of 1.0–1.2 μm and pump wavelength $\lambda_p$. The laser was passively $Q$-switched by a $Cr^{4+}$:YAG saturable absorber with initial transmission $T$ = 80%, which was placed near the output mirror M2. The plane-parallel faces of the absorber were also antireflection coated for the wavelength range 1.0–1.2 μm.

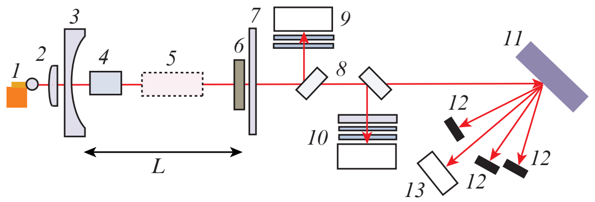


**Figure 1.** Scheme of the experiment:
(*1*) laser diode; (*2*) elements of the pumping system; (*3*) spherical mirror M1; (*4*) Nd:KGW crystal; (*5*) KGW crystal; (*6*) $Cr^{4+}$:YAG saturable absorber; (*7*) plane mirror M2; (*8*) beam splitters; (*9*) CCD camera for a wavelength of 1067 nm with light filters; (*10*) CCD camera for a wavelength of 1181 nm with light filters and a dichroic mirror reflecting radiation at 1067 nm; (*11*) diffraction grating; (*12*) protective screens cutting off radiation at 811, 1067, and 1320 nm (second Stokes component); (*13*) InGaAs photodetector with a band of 5 GHz. The KGW crystal, protective screens, and photodetector are used only in the second experiment.

The cavity configuration was changed by changing its length within the stability region. For this purpose, the output mirror M2 and the $Cr^{4+}$:YAG saturable absorber were mounted on a motorised translation stage, which made it possible to change the cavity length $L$ from 50 to 150 mm with an accuracy of 2.5 μm. Pumping was performed by a quasi-cw laser diode ($\lambda_p$ = 811 nm) with a duty cycle of 20% to decrease the thermal load on the AE. The pump radiation was focused in the AE into a spot about 220 μm in diameter, which provided the pump inhomogeneity factor $\varsigma \approx 1.9-2.0$. The polarisation of radiation at a wavelength of 1067 nm coincided with the optical axis of the Nd:KGW crystal ($E \parallel N_m$)to achieve efficient conversion of laser radiation with $\lambda_g$ = 1067 nm to the first Stokes component with wavelength $\lambda_{S1}$ = 1181 nm (the shift from the fundamental component is 901.5 $cm^{-1}$) [16].

In the first experiment, we measured the lasing thresholds and intensity distributions of radiation with wavelengths of 1067 and 1181 nm with changing the cavity length (this experiment was performed without a KGW crystal). The intensity distribution and lasing threshold at 1067 nm were recorded using a Thorlabs BC106-VIS CCD camera positioned at a distance of about 30 cm from the output mirror. To measure the intensity distribution and the lasing threshold at 1181 nm, we used a BeamOn VIS-NIR CCD camera spaced by ~40 cm from the output mirror. In front of the CCD camera, we placed a dichroic mirror highly reflecting for the 1067-nm wavelength and transparent for $\lambda_{S1}$ = 1181 nm.

In the second experiment, to study the possibility of controlling the SRS conversion efficiency, a KGW crystal 24 mm long cut along the $N_p$ optical axis, which corresponds to the [010] crystallographic axis, was placed in the cavity (Fig. 1). The faces of the crystal, which was oriented so that the fundamental component of the laser radiation was polarised parallel to the $N_m$ optical axis, were antireflection coated to the wavelength range of 1.0–1.2 μm. The KGW crystal wrapped in indium foil was mounted in a copper heat sink placed on a translation stage, which made it possible to move the crystal along the optical axis of the cavity. The initial position of the KGW crystal corresponded to the middle of the cavity. The cavity length in this experiment was chosen to satisfy the ratio $r/s$ = 1/3.

Diffraction grating (*11*) (600 lines $mm^{-1}$) spatially separated radiation with different wavelengths. To record pulses with $\lambda_{S1}$ = 1181 nm, the beams with wavelengths of 811, 1067, and 1320 nm (the second Stokes component) reflected from the diffraction grating were cut off by screens (*12*). The temporal characteristics of radiation were recorded using an InGaAs photodiode with a band of 5 GHz and a Lecroy WR6051A oscilloscope with a transmission band of 1 GHz in two channels. The radiation at $\lambda_{S2}$ = 1320 nm was detected on a screen using a night vision device.

## 3. Experimental results and discussion

Figure 2 presents the measured lasing threshold for wavelengths of 1067 and 1181 nm as functions of the cavity length.

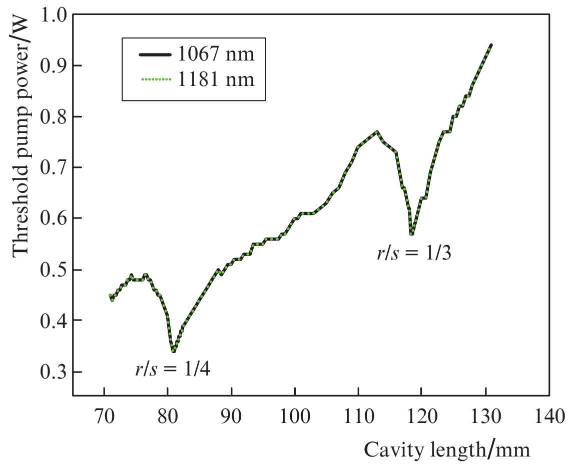


**Figure 2.** Dependence of the threshold pump power absorbed in the $Nd^{3+}$:KGW crystal on the cavity length in the case of the output mirror with reflection coefficients $R$ = 99.9% for 1067 nm and $R$ = 96% for 1181 nm. The lasing thresholds are identical for both wavelengths.

The dependences of the lasing threshold on the cavity length in the regime of $Q$-switching by a saturable absorber coincide for wavelengths of 1067 and 1181 nm. This is explained by the fact that the SRS conversion of the 1067-nm radiation to the first Stokes component occurs sooner than the 1067-nm radiation intensity reaches a value sufficient for bleaching the saturable absorber. At cavity configurations corresponding to ratios $r/s$ = 1/3 and 1/4 under transverse mode locking conditions, the beams with wavelengths of 1067 and 1181 nm narrow to the size of the pump beam in the region of the AE positioned near mirror M1. This leads to a decrease in the lasing threshold at both wavelengths. In this case, the recorded spatial distribution of laser radiation at these wavelengths takes a characteristic ring structure, which testifies to the transverse mode locking for both radiation components.

Figure 3 shows the radiation distribution at wavelengths of 1067 and 1181 nm for the cavity configuration with $r/s$ = 1/4 and at a mismatch from this configuration. One can see that, at $r/s$ = 1/4, the radiation has a ring structure characteristic for transverse mode locking (Figs 3a, 3b), but the beam profile becomes Gaussian at a mismatch from this configuration by 6 mm (Figs 3c, 3d).

In the second experiment, we studied the possibility of controlling the SRS conversion efficiency under conditions of transverse mode locking in a passively mode-locked Nd : KQW laser. It was shown in [5] that the field amplitude inside a cavity under conditions of transverse mode locking depends on the longitudinal coordinate. If the cavity length corresponds to the configuration with the odd ratio $r/s$ = 1/3, the power density on the cavity axis will increase with displacement from the middle of the cavity to the plane or spherical mirror. Because of this, the initial position of the KGW crystal in the cavity corresponded to the middle of cavity, i.e., to the region of a wide transverse field distribution. Then, the crystal was moved with a step of 2 mm to the output mirror using the translation table, which increased the intensity of the field with a wavelength of 1067 nm in the KGW crystal. In this case, we observed a considerable increase in the amplitude of the first Stokes component and, hence, in the SRS conversion efficiency (Fig. 4a).

The saturation of the pulse's amplitude at 1181 nm, observed in Fig. 4a with moving the crystal to the output cavity mirror (to the region of a higher fundamental radiation intensity), which begins from the displacement of 6 mm from the cavity centre, is explained by the development of cascade generation of the second Stokes component.

A typical oscillogram of a train of 1181-nm Stokes pulses is presented in Fig. 4b. Note that the time interval between pulses (1.1 ns) corresponds to the cavity roundtrip time, which testifies to self-locking of longitudinal modes, while the high modulation depth indicates complete mode locking.

## 4. Conclusions

Intracavity SRS self-conversion in a diode end-pumped laser based on Nd : KGW/$Cr^{4+}$ : YAG crystals is studied under conditions of transverse mode locking. It is found that, under conditions of transverse mode locking of the fundamental laser radiation at 1067 nm, there also occurs transverse mode locking of the first Stokes component at 1181 nm. It is shown that, in the transverse mode locking regime, it is possible to control in large measure the efficiency of SRS conversion of the fundamental radiation to the first Stokes component by chancing the position of an additional KGW crystal inside the cavity with the ratio $r/s$ = 1/3. In this case, transverse mode locking is accompanied by complete locking of longitudinal laser modes at wavelength of 1067 and 1181 nm.

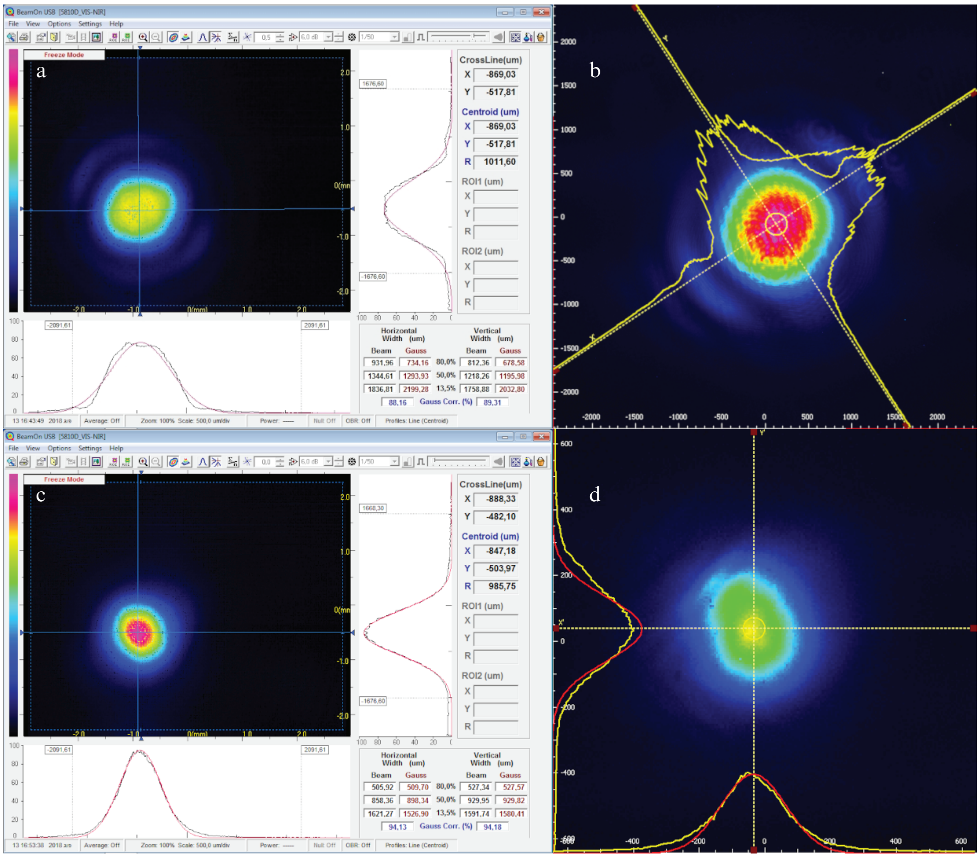


**Figure 3.** (Coulor online) Spatial structure of radiation at wavelengths of (a, c) 1181 and (b, d) 1067 nm (a, b) under conditions of transverse mode locking ($r/s$ = 1/4) and (b, d) at a 6-mm displacement from the transverse mode locking region.

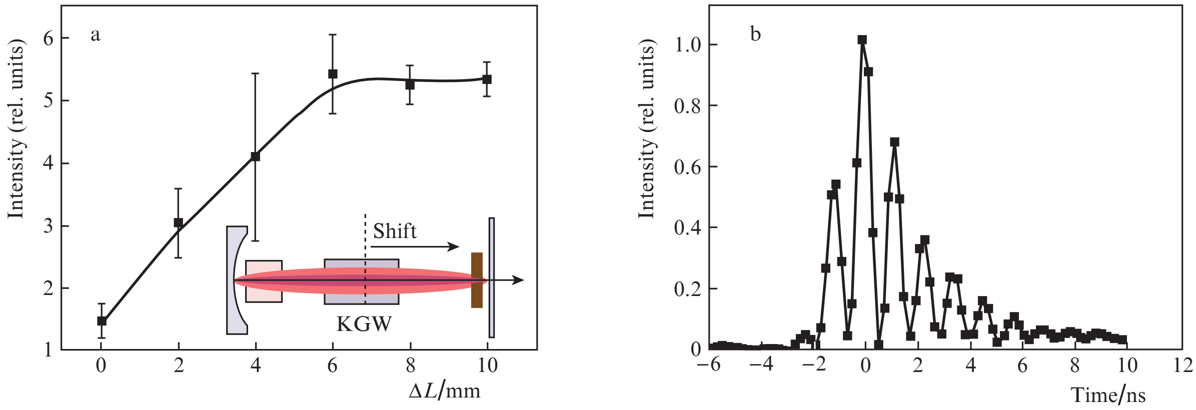


**Figure 4.** (a) Dependence of the amplitude of the first Stokes pulses on the shift $\Delta L$ of the KGW crystal to the output mirror and (b) typical oscillogram of the first Stokes pulses ($\Delta L = 0$ corresponds to the position of the crystal centre in the middle of the cavity).

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