ment by DOE of the views expressed in this article.

CTuM71
Diode-pumped cw laser around 1.54 µm using Yb, Er-doped silico-boro-phosphate glass
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Erbium lasers in the eye-safe region around 1.55-µm wavelength exhibit many applications such as measuring techniques, LIDAR systems, and data transfer via glass fibers. The highest slope efficiencies of an Er 1.55-µm laser have been reported for an Yb, Er-doped glass. In the present work the laser properties of Yb, Er-doped silico-boro-phosphate glasses containing high Yb concentrations were investigated under longitudinal diode pumping. These glasses were already used for transverse diode excitation. Laser action of similar glasses has also been reported for longitudinal pumping, but only with low output power.

During the laser experiments summarized in Table 1 the glasses were pumped around 970 nm wavelength with two InGaAs laser diodes coupled with a polarizing beam splitter. A hemispheric resonator with an output mirror of 1% [Fig. 1 (a)]. The glasses exhibited thermal problems, and the surfaces were damaged at high pump powers.

The 2-mm-long Yb(4·1014 cm⁻³), Er(5·10¹⁹ cm⁻³);glass was also pumped with a 3.7-W pigtial laser diode. The diameter of the fiber was 100 µm. Using collimating and focusing lenses of f₉₀₀ = 25 mm and f₉₀₀ = 50 mm, hence an enlarged pump focus, the maximum cw and quasi-cw (duty cycle 50%) output powers and slope efficiencies were P_{out,cw} = 353 mW, P_{out,qcw} = 706 mW, η_{cw} = 25.8%, and η_{qcw} = 28.3% [Fig. 1(b)].

In further experiments the cooling as well as the Yb and Er concentrations have to be optimized for an improvement of the laser performance. In addition, the damage threshold should be increased in order to allow higher pump levels.

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CTuM71 Table 1. Results of the Laser Experiments on Yb, Er-doped Silico-boro-phosphate Glasses with 4·10¹⁴ cm⁻³ Yb

<table>
<thead>
<tr>
<th>Er concentration [cm⁻³]</th>
<th>d [mm]</th>
<th>f [cm] mode</th>
<th>P_{out}[mW] (HR)</th>
<th>P_{out}[mW] (T = 1%)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>2</td>
<td>cw</td>
<td>28</td>
<td>115.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>qcw</td>
<td>31</td>
<td>177.0</td>
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<td>3</td>
<td>cw</td>
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<td>110.2</td>
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<td>97</td>
<td>106.0</td>
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<tr>
<td></td>
<td>3</td>
<td>qcw</td>
<td>52</td>
<td>154.3</td>
</tr>
</tbody>
</table>

CTuM72
V:YAG as passive Q-switch at 1342 nm and 1064 nm
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Passive Q-switching has provided a very successful, compact, means of generating short, high intensity pulses. Many of the saturable absorbers used have been based on materials doped with the Cr⁴⁺ ion, in particular Cr:YAG, which has yielded pulses of 600-ps duration and peak power in excess of 28 kW, in a microchip geometry with Nd:YAG. The saturable absorption of the Cr⁴⁺ ion falls off beyond 1.1 µm, restricting its application to wavelengths shorter than this. More recently the use of multiple quantum well semiconductor devices has produced ultrashort pulses, 230 ps at 1342 nm and 56 ps at 1064 nm using Nd:YVO₄ in a microchip format. These SESAM devices however have high loss, giving low pulse energies, and their low damage threshold limits their scalability.

Here we believe we report the first use of V:YAG as a passive Q-switch for a diode-pumped Nd³⁺ laser at 1 µm and 1.3 µm. Previous investigations of the excited states and saturation of V:YAG showed that this crystal can be successfully used as a saturable absorber for pulsed lasers operating in the red and infrared spectral regions. The V:YAG crystal used for our work was a 3-mm-long cylinder, with a V⁺⁺ doping concentration of 2·10¹⁹ atoms/cm³ and had a wedge of 4 mrad between the crystal faces. The crystal carried a broadband AR coating. The small signal transmission of the crystal was 95.5% at 1064 nm and 92.2% at 1342 nm with less than 1% reflection from the coatings.

The 1342-nm laser consisted of a 1%-doped 3·5·10¹⁹ atoms/cm³ Nd:YVO₄ coated HR/AR at 1342 nm, an air gap of 0.55 mm from the V:YAG crystal, and a discrete output coupler, giving a total cavity length of 4 mm. The 1064-nm laser used for its gain material a 3%-doped 3·5·10¹⁹ atoms/cm³ crystal of Nd:YVO₄ coated HR/AR at 1064 nm as the gain material and suitable discrete output couplers. A 2-W laser diode was used to pump this arrangement through a 8-mm collimating lens and 8-mm focussing lens. No attempt was made to shape the diode beam to optimize coupling or to double pass the pump light through the gain crystals.

At 1064 nm the relatively low loss of the satu-
CTuM72 Fig. 1. Operation of Nd:YVO₄ passively Q-switched by V:YAG at 1342 nm. (Peak power—triangles, pulse FWHM — squares). The cavity length was 4 mm, composed of a 3 × 3 × 0.5 mm 1%-doped Nd:YVO₄ crystal, 3-mm piece of V:YAG and a 2.5% output coupler.

CTuM73 Fig. 1. Raman spectra of sapphire and LiSGaF in the (az) scattering geometry. The weak spectrum of sapphire has been offset for visibility.

CTuM73 Fig. 2. Plots of the function $S(\tau)$ (see text for explanation) for Cr:LiSGaF and Ti:sapphire.

CTuM73 Fig. 3. Raman spectrum of relevant to ultrashort pulse generation vibrational modes in YAG.

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Pastoral absorber and its low saturation intensity lead to pulses at a repetition rate of up to 1 MHz, pulse durations of 22 ns and peak powers of only 20 W. With optimization and a higher $V^+$ doping concentration it is hoped results comparable to the use of Cr:YAG should be attainable. Much greater success was obtained at 1342 nm; the measured powers in the passively Q-switched operation of this system at 1342 nm are shown in Fig. 1. At 1342 nm pulses as short as 9.3 ns with peak powers in excess of 350 W were obtained. Single-pass doubling of the 1342 nm in a piece of 3 × 3 × 2 mm LBO gave 5.4-ns pulses and peak powers of 25 W.

Following these encouraging initial results, we will present work on the optimization of V:YAG as a passive Q-switch at 1342 nm and 1064 nm.

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CTuM73 Raman-induced pulse self-frequency shift in crystalline ultrashort pulsed mode-locked lasers

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The ultrashort pulse spectra, offset to the red from the maximum of the gain spectrum, were published in several papers on Ti:sapphire$^{1-3}$ as well as Cr:LiSAF$^{4}$ and Cr:YAG$^{5}$ mode-locked lasers. The red shift was either explained by dispersion effects or left without discussion. Recently we reported an infrared pulse self-frequency shift in Cr:LiSAF and Cr:LiSGaF lasers$^{6}$ suggesting an alternative mechanism, based on induced Raman scattering as a first-order nonlinear perturbation, directly influencing the spectral position of the pulse.

In this paper we present the results of experimental investigation of this phenomenon (mode-locking experiments and Raman gain measurements) in crystals, commonly used in mode-locked lasers (e.g., Ti:sapphire, Cr:LiSAF, Cr:LiSGaF, Cr:YAG, etc.) and compare them with the theory.

The Raman-induced self-frequency shift $\Delta \nu$ per one Raman line is given by

$$\Delta \nu = -\frac{3k^2}{128g^2g_0^2} \frac{\omega^2 \Omega^2 L}{2}$$

where $g_0$ is the Raman gain, $\Delta \nu_0$ is the Raman linewidth, $\Omega$ is the laser bandwidth, $(\omega \nu \kappa)$ is a convolution of the pulse and the Raman spectrum, $L$ is the crystal length, and $A$ is the beam cross section in the crystal.

The $g_0$ data for crystals of interest could not be found in the literature. Therefore, we measured the spontaneous Raman spectra using the confocal backscattering geometry and correspondingly orientated undoped samples. This allowed to separate those Raman lines, which produce the shift in the laser crystals, and calculate the respective $g_0$ and $\Delta \nu_0$ values. The $g_0$ of the crystalline quartz$^2$ was used as a reference.

Figures 1 and 2 compare the spontaneous Raman spectra of LiSGaF and sapphire, as well as the calculated material-dependent part of (1) summing the contributions from all spectral lines $S(\tau) = \sum g_{0,\nu} G(\omega, \nu, \tau)$ for Cr:LiSGaF and Ti:sapphire.

Substituting other experimental parameters for our Cr:LiSGaF laser we get $\Delta \nu \sim 85$ nm at $\tau$ around 20 fs (i.e., close to the maximum of the curve in Fig. 1), which agrees well with mode-locking experiments. We may also conclude from Fig. 1 that the Raman shift of the sub-10-fs pulses in both crystals is considerably smaller than that in 20-fs regime, which agrees with the published data on Ti:Sapphire.$^2$ As another example, Fig. 2 presents a rich Raman spectrum of undoped YAG containing a number of strong lines in the low frequency range. This is a likely explanation for a significant (~50 nm) red shift of the femtosecond Cr:YAG observed already at pulse durations of ~50 fs.

In conclusion, we believe that we understand the nature of the pulse self-frequency shift and found a good agreement of experiments with the theory. Comparing Ti:sapphire, Cr:LiSAF, Cr:LiSGaF, and Cr:YAG crystals, we found the Raman response of Ti: sapphire to be the smallest. Raman gain measurements predict also a considerable frequency shift in Cr:YAG mode-locked lasers. The most remarkable feature of the frequency-shift phenomenon in crystalline media as opposed to glass fibers is the pronounced maximum at a certain pulse duration (e.g., around 20 fs in Ti:sapphire), depending upon the vibrational spectrum of the host. Finally, we believe to have found one more factor, setting the limits on the shortest achievable pulse duration in ultrashort pulsed solid-state lasers.

It is a pleasure to thank A. Cassanho, H.P. Jenssen, and H.G. Gallagher for providing the undoped crystal samples for this research.