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Temperature-dependent spectroscopy and microchip laser operation of Nd:KGd$(WO_4)_2$

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ABSTRACT

High-resolution absorption and stimulated-emission cross-section spectra are presented for monoclinic Nd:KGd$(WO_4)_2$ (Nd:KGW) laser crystals in the temperature range 77–450 K. At room-temperature, the maximum stimulated emission cross-section is $\sigma_{SE} = 21.4 \times 10^{-20}$ cm^2 at 1067.3 nm, for light polarization $E \parallel N_m$. The lifetime of the $^4F_{3/2}$ state of Nd^{3+} in KGW is practically temperature independent at 115 ± 5 μs. Measurement of the energy transfer upconversion parameter for a 3 at.% Nd:KGW crystal proved that this was significantly smaller than for alternative hosts, ~2.5×10^{-17} cm^3/s. When cut along the N_g optical indicatrix axis, the Nd:KGW crystal was configured as a microchip laser, generating ~4 W of continuous-wave output at 1067 nm with a slope efficiency of 61% under diode-pumping. Using a highly-doped (10 at.%) Nd:KGW crystal, the slope efficiency reached 71% and 74% when pumped with a laser diode and a Ti:Sapphire laser, respectively. The concept of an ultrathin (250 μm) Nd:KGW microchip laser sandwiched between two synthetic diamond heat-spreaders is demonstrated.

1. Introduction

Monoclinic double tungstates, KRE$(WO_4)_2$, where RE stands for an optically passive rare-earth element like Gd, Y or Lu, are exceptionally suitable for doping with active rare-earth ions like Nd^{3+}, Yb^{3+}, Tm^{3+} or Ho^{3+} [1]. Such host-dopant combinations offer intense and broad absorption and emission bands with a strong polarization-anisotropy [2,3], high doping concentrations without significant luminescence quenching [4], and they are Raman-active [5]. The thermal conductivity of double tungstates (~3 W/m.K) is three times higher than that of laser glasses [6]. As a result, medium-power but highly efficient continuous-wave (CW) [7,8], Q-switched [9,10] and mode-locked [11,12] double tungstate lasers utilizing various geometries of the active element (e.g., bulk, slab, thin-disk) have been reported to date.

The unique combination of attractive spectroscopic properties and high RE doping make the double tungstates very interesting for microchip lasers [13]. Such lasers consist of a gain medium and optionally a saturable absorber for Q-switching placed in a plano-plano laser cavity without air gaps. The compact, robust and low-loss design provides high laser efficiency [13]. However, the possibility to exploit the advantages of double tungstates in the microchip geometry was hampered for many years by the negative thermal lens of these materials [14] resulting mainly from negative thermo-optic coefficients [15]. Recently, a crystal orientation was determined that can provide access both to the high-gain laser polarizations and a positive thermal lens, independent of the active ion [8,16,17]. This orientation is realized by cutting along one of the principal axes of the optical indicatrix of these biaxial crystals (N_g-axis). As a result, highly-efficient Yb, Tm and Ho double tungstate microchip lasers were reported recently [18–20].

The implementation of a Nd-doped double tungstate microchip as active medium is of great interest as it can fully exploit the

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advantage of the 4-level laser medium, i.e. very low laser threshold in a low-loss microchip cavity resulting in high optical-to-optical laser efficiency. Among the double tungstates, $KGd(WO_4)_2$ (commonly shortened to KGW) is the best host for Nd^{3+} doping due to the similarity of the ionic radii of eight-fold oxygen-coordinated Gd^{3+} (1.053 Å) and Nd^{3+} (1.109 Å). Thus, doping up to 10 at.% Nd is possible, whilst it is limited to ~2 at.% for KYW and KLuW host crystals.

To date, studies of Nd:KGW have focused mainly on the development of efficient low-threshold lasers emitting at ~1 μm and 1.35 μm [21,22]. Nd:KGW is an interesting laser crystal for several other reasons. First, the main laser transition of Nd^{3+} ions in KGW ($^4F_{3/2} \rightarrow {}^4I_{11/2}$) generates a wavelength (~1067 nm) that is slightly longer than that of Nd:YAG and Nd:YVO_4 (~1064 nm). If frequency doubled, this corresponds to a green emission at 533.6 nm, which is exceptionally suitable for pumping of visible (deep-red, ~702 nm) Eu^{3+} lasers [23]. In addition, it can be used for in-band pumping of green upconversion Ho^{3+} lasers (to the $^5F_4$+$^5S_2$ state). Secondly, KGW is a well-known Raman-active material with an intense vibrational mode at 901 cm^{-1} that enabled the operation of a CW Nd:KGW Raman laser [5]. The combination of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ emission with self-Raman conversion and second-harmonic generation can produce yellow light sources (at ~590 nm). In addition, Raman conversion of the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ emission (~1351 nm) can lead to the generation in the eye-safe spectral region at ~1540 nm. Finally, in comparison with Nd:YAG and Nd:YVO_4 crystals, Nd:KGW has much broader absorption bands at 808 nm [24]. The latter, together with the higher achievable Nd^{3+} concentrations mentioned above, makes Nd:KGW lasers almost insensitive to temperature drift of the pump diode wavelength – a feature, successfully exploited in a ChemCam laser system, developed for space applications [25].

In the present work, we aim to exploit the spectroscopic and thermo-optic features of Nd:KGW for microchip laser operation. Detailed reconsideration of spectroscopic properties of Nd:KGW is motivated by a discrepancy in the results reported to date [26,27], as well as the lack of information with regard to temperature-dependence of the absorption and stimulated-emission (SE) cross-sections for low and elevated temperatures. The former are of practical importance for cryogenic lasers, a concept that can mitigate the main drawback of Nd:KGW (i.e., strong thermo-optic aberrations). The latter are useful for understanding the effects of strongly localized heating produced by the dissipation of pump power in Nd:KGW lasers. Moreover, the dependence of SE cross-sections on temperature has been utilized for significant energy scaling in Q-switched Nd:YVO_4 microchip formats [28], simply by increasing the temperature of the laser gain material. With a lower SE cross-section and similar lifetime, Nd:KGW has the potential for even higher pulse energies than Nd:YVO_4 using compact Q-switched microchip laser cavities at elevated temperatures of the gain material. Therefore, detailed information on the temperature-dependence of the SE cross-sections in Nd:KGW is essential for the development of compact Q-switched lasers based on this crystal. Finally, we present the first CW laser action of ultrathin (250 μm) Nd:KGW crystal sandwiched between two diamond heat-spreaders as an initial step towards realization of such microchip lasers.

2. Optical spectroscopy

For the spectroscopic studies, we used 1 mm-thick 3 and 4 at.% Nd:KGW crystals (N_{Nd} = 1.9 and 2.5 × 10^{20} at./cm^3, respectively). The 3 at.% crystal was cut along the N_g-axis of the optical indicatrix (the orientation that is of interest for microchip laser operation) thus providing access to the two other principal light polarization states, $E \parallel N_m$ and N_p. The second crystal was N_m-cut, providing access to $E \parallel N_g$ and N_p emission.

For the absorption measurements, undertaken with the 3 at.% sample, a broadband amplified spontaneous emission (ASE) source, a polarizer, and an optical spectrum analyzer (OSA) with 0.1 nm resolution were used. The experimental setup is shown in Fig. 1. Two different fiber-coupled (fiber diameter: 200 μm, N.A. = 0.22) light sources were employed. One of the sources was a diode laser with a nominal lasing wavelength of 805 nm (LIMO60-F200-DL808); however, operation below the laser threshold delivered ~100 mW of ASE covering the wavelength range 780–840 nm. The second source, an 870 nm high-power light-emitting diode (LED) (JET-870-05 Roithner Lasertechnik) produced ~10 mW of output power at the exit facet with an emission spectrum covering 850–910 nm. Both probe light sources were coupled into a measurement fiber. The exit facet of the latter was fixed in position and imaged in the sample with three times magnification. The light transmitted through the sample was subsequently re-imaged onto the endface of a fiber patch cable and sent to an OSA (ANDO AQ6317B). A broadband cube polarizer was used to isolate the respective principal optical polarization of interest, $\parallel N_m$ and $\parallel N_p$. Fig. 2 illustrates emission spectra for both ASE sources measured before and after the Nd:KGW crystal.

Absorption spectra for the Nd:KGW crystal corresponding to the $^4I_{9/2} \rightarrow {}^4F_{5/2}$ and $^4I_{9/2} \rightarrow {}^4F_{3/2}$ transitions, measured at room temperature (300 K), are shown in Fig. 3(a) for the studied polarization states, $E \parallel N_m$ and N_p. For both transitions, a significant anisotropy is detected with the larger absorption cross-sections (σ_{abs}) corresponding to $E \parallel N_m$. For the $^4I_{9/2} \rightarrow {}^4F_{5/2}$ transition and light polarization $E \parallel N_m$, the absorption band contains an intense peak with a maximum $\sigma_{abs}(m) = 29 \times 10^{-20}$ cm^2 at 810.5 nm and a full width at half maximum (FWHM) of 1.7 nm. For $E \parallel N_p$, this band contains two peaks of similar intensity centered at 806.2 and 810.5 nm with their maxima $\sigma_{abs}(p)$ ~6×10^{-20} cm^2. For the $^4I_{9/2} \rightarrow {}^4F_{3/2}$ transition and both polarizations, the absorption band contains two intense peaks centered at 875.7 nm (FWHM = 2.3 nm) and 883.8 nm (FWHM = 1.6 nm). The second peak dominates and the corresponding values for the maximum absorption cross-sections are $\sigma_{abs}(m) = 8.8$ and $\sigma_{abs}(p) = 4.8 \times 10^{-20}$ cm^2.

As the strongest absorption in Nd:KGW corresponds to the polarization state $E \parallel N_m$, we have performed temperature-dependent measurements for this polarization alone. However, for the $^4I_{9/2} \rightarrow {}^4F_{5/2}$ transition at low temperatures, we were limited by the very strong absorbance of the 1 mm-thick crystal, so the measurements for this transition were only conducted for the 300–450 K range, Fig. 3(b). At the maximum elevated temperature tested (450 K), the $\sigma_{abs}(m)$ peak decreased by a factor of 1.8, as compared with its room-temperature value, while the FWHM bandwidth slightly increased to 2.7 nm.

For the $^4I_{9/2} \rightarrow {}^4F_{3/2}$ transition, limitation of strong absorption can be overcome by fitting the spectral shape of the local peaks with a Lorentzian function, as can be expected for Raman

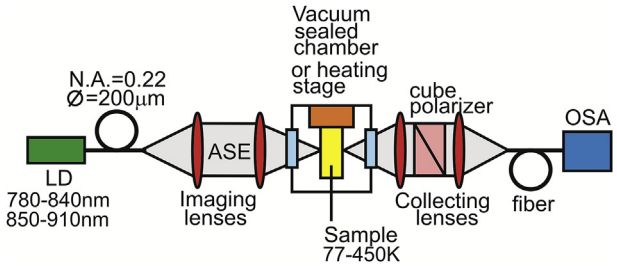

Fig. 1. Set-up for temperature-dependent absorption measurements: LD – laser diode, ASE – amplified spontaneous emission, OSA – optical spectrum analyzer.