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Emission properties of a Tm^{3+}:$GdVO_4$ microchip laser at 1.9 μm

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Abstract. $GdVO_4$ as a host for thulium has several advantages for diode pumping in comparison with other crystals. The absorption cross section of thulium in $GdVO_4$ is considerably stronger and broader than in YAG and YLF and the spectrum is shifted closer to the emission wavelength of commercially available AlGaAs laser diodes. In our paper, we report on the temporal and spectral emission properties of a monolithical Tm^{3+}(6.9 at. %):$GdVO_4$ microchip laser at 1.9 μm. The laser can be adjusted to emit either cw or in an oscillating regime. Slope efficiencies up to 47% are achieved. This value exceeds the Stokes limit of 42%.

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Eye-save lasers on the $^3F_4 \rightarrow {}^3H_6$ transition in Tm^{3+} ions emitting at 2 μm are of considerable topical interest, having potential use in various applications such as altimetry, in atmospheric remote sensing including Doppler LIDAR wind sensing, as well as water vapour profiling by differential absorption LIDAR. Although, thulium is a well known activator ion in different laser host materials, key problems still remain. These include severe dependence on pump diode temperature control due to the relatively narrow Tm absorption bands in YAG and YLF. In the case of longitudinal pumping, a further drawback of YAG and YLF is the requirement of low numerical aperture pump beams for efficient overlap of pump and resonator modes over the relatively long crystal lengths. Crystal length is dictated by the low absorption in these materials. In addition, the Tm absorption peaks are shifted to shorter wavelengths with respect to neodymium, for which the bulk of commercially available diode lasers are prepared. Therefore, cooling to sub-zero temperatures is often required.

The use of $GdVO_4$ as host crystal offers possible solutions to these problems. The absorption cross section of thulium in $GdVO_4$ is considerably stronger ($\alpha_{peak} = 25\,cm^{-1}$ in Tm(6.9 at. %):$GdVO_4$, E ∥ c) and broader (770 nm – 820 nm) than in YAG and the spectrum is shifted closer to the emission wavelength of commercially available AlGaAs laser diodes [1, 2]. The broad emission spectrum (1.9 μm – 2.1 μm) [1, 2] allows for tuning the laser wavelength and for generating short pulses. Furthermore, the large thermal conductivity of $GdVO_4$ ($10\,Wm^{-1}K^{-1}$ at 300 K) is very favourable for efficient cooling of the crystal. In spite of all these promising properties of $GdVO_4$, there are only two reports on laser action in a Tm:$GdVO_4$ crystal [1, 3]. The temporal and spectral emission properties of this laser are not yet studied. In Tm^{3+}-doped crystals slope efficiencies exceeding the Stokes limit can be realised [4]. This has been demonstrated in a Tm:$GdVO_4$ crystal only during a very short time [1]. In a stable configuration, however, only slope efficiencies up to 36% are realised as yet [1].

In our paper we report on a monolithical Tm^{3+}:$GdVO_4$ microchip laser at 1.9 μm. The temporal and the spectral emission properties are studied. Two different temporal regimes are discussed. Furthermore, slope efficiencies exceeding the Stokes limit of 42% are achieved.

1 Experimental setup

The experimental arrangement is shown in Fig. 1. A Ti:sapphire laser (Spectra-Physics 3900) is pumped with an argon-ion laser (Spectra Physics 2570 E). Since the absorption peak

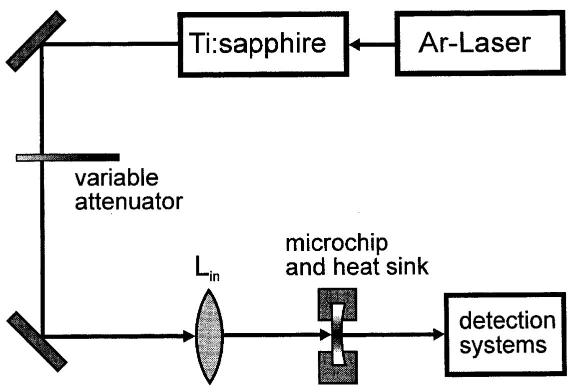

Fig. 1. Experimental arrangement. The resonator consists of a monolithical Tm^{3+}(6.9 at. %):$GdVO_4$ microchip laser with mirrors of $R_{in} = 99.8\%$ and $R_{out} = 97.6\%$

of the $^3F_4$ level is located at 797 nm [1, 2], the Ti:sapphire laser is tuned to emit at this wavelength. With a neutral density filter of variable transmission the beam is attenuated to control the input power. Lenses L_{in} ($f_1 = 50$ mm, $f_2 = 72$ mm, $f_3 = 100$ mm) are used to focus the pump beam onto the front surface of the crystal. The waist of the pump beam at the crystal front face is $r_1 = 8.5$ µm, $r_2 = 12$ µm, and $r_3 = 17$ µm, respectively. Due to the high absorption cross section in *c*-axis polarisation [1, 2], the electric field vector of the linearly polarised pump beam is tuned to be parallel to the *c* axis of the crystal. The resonator consists of a monolithical Tm:$GdVO_4$ microchip mounted on an copper heat sink (1.6 cm × 1.6 cm × 1.0 cm). The heat sink ($T = 5$ °C) ensures a proper cooling of the crystal. The thermal contact between the heat sink and the microchip is enhanced by heat conductivity paste. The sample was grown at the General Physics Institute in Moscow by the Czochralski technique. The Tm(6.9 at. %):$GdVO_4$ crystal with lateral dimensions of 5 mm × 5 mm is cut perpendicular to the *a* axis. The length of the cavity is fixed by the length of the crystal of $L = 1$ mm. This yields an effective length of the resonator, considering the refractive index of $GdVO_4$ ($n_e = 2.17$, $n_o = 1.96$) of $L_{reso} \approx 2$ mm. In view of future investigations with a high-power diode-laser pump source the back surface is concave with a radius of curvature of $\rho = 500$ cm to partially compensate the thermal lens. The mirrors are directly coated onto the surfaces of the crystal. The incoupling mirror transmits 98% at the pump wavelength and reflects more than 99.8% at the laser wavelength. The mirror on the back surface of the crystal transmits 2.4% at 2.0 µm and reflects 99.8% at 800 nm.

A filter blocks the residual pump power. The beam is detected with either a power meter (Sensor Physics), an InAs diode (temporal resolution ≈ 8 ns), or a monochromator (Spectra Pro 500) (resolution ≈ 0.2 nm) in connection with a PbS detector (Ealing Beck 28-7870).

2 Experimental results

2.1 Input–output characteristics

The cw laser output power as a function of absorbed pump power is shown in Fig. 2 for different focal lengths of the incoupling lens. With increasing focal length of $f = 50$ mm, 72 mm, and 100 mm increasing thresholds of $P_{th} = 380$ mW, 470 mW, and 580 mW result. The slope efficiencies are $\eta =$ 24%, 40%, and 47%, respectively. The slope efficiency of $\eta =$ 47% exceeds the Stokes limit of $\eta_{st} = \lambda_{pump}/\lambda_{laser} = 42\%$.

The microchip laser is geometrically unstable at zero pump power. With increasing pump power the pump beam induces a thermal lens. For low pump power the laser cavity is nearly a Fabry–Pérot resonator and the beam waist radius has a diameter of some millimetres. With increasing pump power, the laser mode diameter reduces to approximately 200 µm ($P \approx 1$ W). The exact beam propagation characteristics of the Tm:$GdVO_4$ microchip laser are the subject of future investigations. In [5] the waist radius and the divergence angle of the emission of a Nd:$GdVO_4$ microchip laser is studied.

For pump powers available to us, the waist of the resonator mode is much larger than the pump beam waist. The increase in slope efficiency with increasing focal length is mainly due to the matching of resonator mode and pump mode. Increasing the focal length of the incoupling lens enlarges the radius of the focus of the pump mode, and the pump beam matches better the resonator mode.

The high slope efficiency results from a cross-relaxation which is populating the upper laser level. The energy level scheme of Tm^{3+} is shown in Fig. 3. The Tm^{3+} ions are pumped at 797 nm wavelength by ground-state absorption ($^3H_6 \rightarrow {}^3H_4$). The upper laser level ($^3F_4$) level is populated by subsequent radiative and non-radiative decay. Furthermore, the $^3F_4$ level can be populated via the cross-relaxation $^3H_4 + {}^3H_6 \rightarrow {}^3F_4 + {}^3F_4$. The efficiency of this process increases with the dopant concentration. In Tm^{3+}:YAG this cross-relaxation completely dominates the decay from the $^3H_4$ level at concentrations above 8×10^{20} cm^{-3} (5.7 at. %) [6]. The quantum efficiency of this process is 2 and therefore, the theoretical limit for the slope efficiency is 83%.

Slope efficiency and threshold of a quasi three-level system depends on the temperature of the crystal *T*. The temperature *T* is measured close to the interface between heat sink and crystal. The temperature *T* is tuned in a range of 30 K. The output power decreases with increasing temperature from 83 mW (279 K) to 33 mW (306 K) [3].

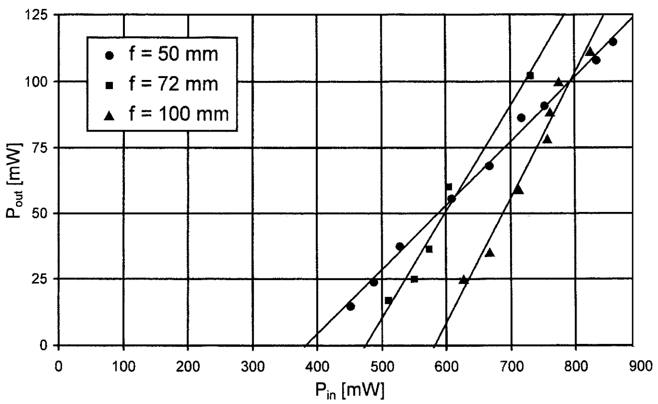

Fig. 2. Output power P_{out} as a function of the absorbed power P_{in} of a Tm:$GdVO_4$ laser at 1.95 µm for three differently focused pump beams. The lowest threshold achieved is 380 mW and the highest slope efficiency is 47%

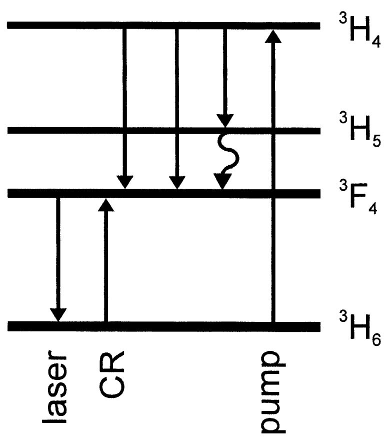

Fig. 3. Energy level scheme of Tm^{3+}. The upper laser level is mainly populated via the cross-relaxation (CR). Therefore, the quantum efficiency of the Tm laser is larger than 1 and slope efficiencies exceeding the Stokes limit can be achieved

The threshold is measured for two different pump wavelengths. The peak in the absorption spectrum of Tm:$GdVO_4$ is located at 797 nm [2]. Pumping at this wavelength yields a threshold of 670 mW. Commercially available laser diode pump sources emit around 806 nm. At this wavelength the threshold is 790 mW. Due to the broad absorption spectrum of Tm (770 nm − 820 nm) [1] in $GdVO_4$, the dependence of the pump wavelength on the threshold is only small.

2.2 Temporal and spectral behaviour

The temporal behaviour of a Tm^{3+}:$GdVO_4$ laser pulse is shown in Fig. 4a. The pump beam is chopped with a duty cycle of 50% and a frequency of $f = 13$ Hz providing an excitation time of 38 ms. After a short period (≈ 2 ms) of spiking, cw emission is established. The emission spectrum is shown in Fig. 5a. The laser line has a maximum at 1916 nm and has a FWHM of 6 nm. The free spectral range of the resonator is $\Delta\lambda \approx 1$ nm. Therefore, the emission spectrum contains only about six longitudinal modes. Single-frequency operation in a Tm:Ho:YAG at 2.0 μm has been shown in [7].

A slight misalignment in the tilt angle of the crystal leads to laser action not exactly perpendicular to the mirrors. This introduces losses to the cavity. These losses reduce the cavity lifetime and the laser begins to spike nearly undamped (Fig. 4b). The period T of the relaxation oscillation depends on the pump power and is in the order of 1 μs. Due to the increased losses in the cavity, the spectrum (Fig. 5b) is shifted to longer wavelengths with respect to the spectrum of the cw emission. The centre wavelength is located at 1951 nm and the spectrum is broader (FWHM = 16 nm) than in case of cw emission. Many different longitudinal modes with a free spectral range of $\Delta\lambda = 1\,\text{nm} \pm 20\%$ can be distinguished in the spectrum. The free spectral range is given by the effective length of the cavity ($L_{\text{reso}} = 2$ mm). The non-uniformity of the spectrum is due to water absorption lines, which are numerous in this spectral region.

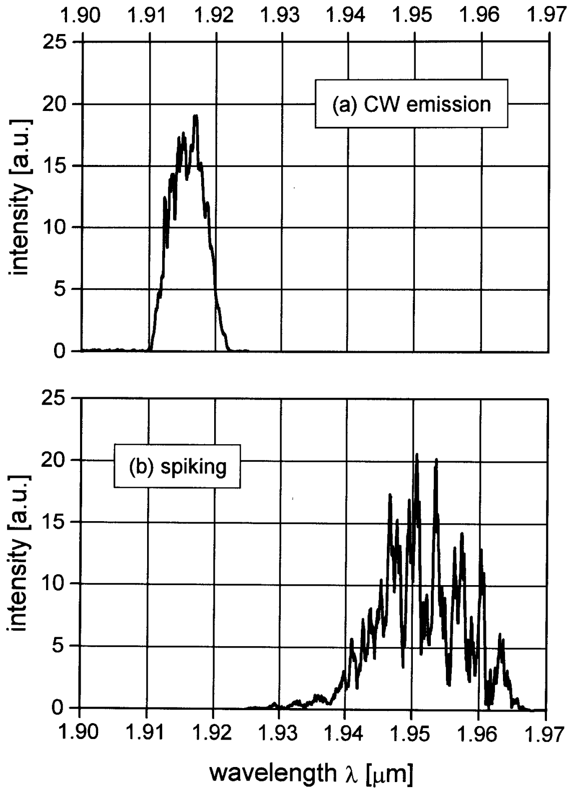

Fig. 5a,b. Spectral behaviour of the laser emission. **a** cw emission: the laser line has a maximum at 1916 nm and has a FWHM of 6 nm. **b** Spiking: The peak is shifted to 1951 nm and the emission is broader (FWHM = 16 nm) than in case of cw emission

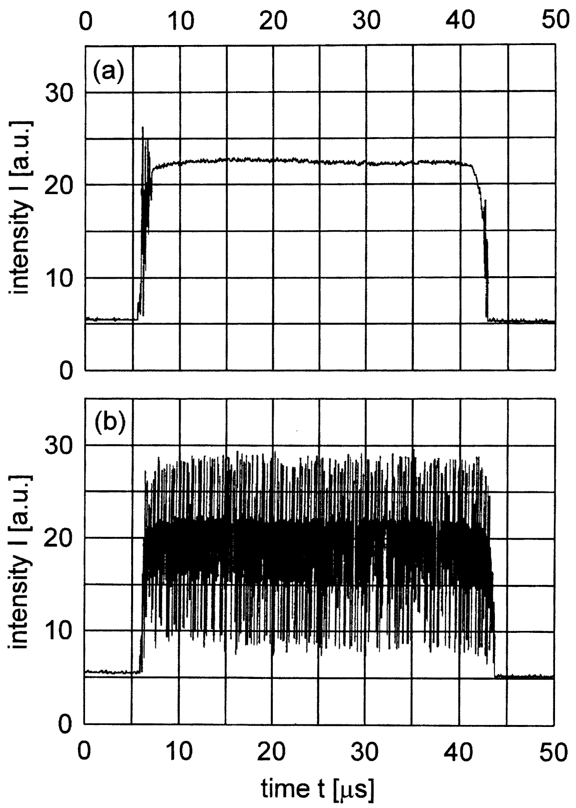

Fig. 4a,b. Temporal behaviour of the laser emission. **a** After a short period of spiking (≈ 2 ms), the laser emits continuous wave. **b** The laser is strongly spiking. cw emission cannot be established

3 Conclusions

A monolithical Tm^{3+}:$GdVO_4$ microchip laser at 1.9 μm has been built. The temporal and the spectral emission properties have been studied. cw emission and an oscillating regime with periods of $T = 1$ μs have been discussed. The spectrum of the cw emission is located around 1916 nm and has a FWHM of 6 nm. The relatively wide spectrum allows for the generation of short pulses and for tuning the emission wavelength. The emission of the laser in the oscillating regime contains various longitudinal modes. The spectrum is shifted to longer wavelengths ($\lambda_c = 1951$ nm) and the spectrum is broader (FWHM = 16 nm) than in case of cw lasing. The input–output curves have been measured for three different focal lengths of the incoupling lenses. The highest slope efficiency obtained is 47% and the lowest threshold achieved is 380 mW. The slope efficiency exceeds the Stokes limit of 42%. This results from a cross-relaxation, which depletes the ground state and populates the upper laser level.

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