The study of a Tm:YLF laser pumped by a Raman shifted Erbium fiber laser at 1678 nm

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A Tm:YLF laser pumped by a Raman shifted Er-fiber laser at 1.678 μm was studied at two Tm3+ ion concentrations equal to 1.5% and 5%. At output powers up to 460 mW the measured lasing efficiency at a wavelength of ~1.93 μm was as high as ~50%. The lasing performance was compared with that obtained under pumping by a 792-nm laser diode. The temporal structure of the laser pulse was recorded and the beam propagation factor M² was measured for all pumping conditions.

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1. Introduction

The most popular solid-state lasers in the wavelength region around 2 μm are based on either Tm3+ or a combination of both Tm3+ and Ho3+ ions. Such lasers are well situated for pumping by diode lasers due to the presence of a wide absorption band in Tm3+ near 792 nm. As a result the pumping of the Tm-lasers is efficient when the Tm concentration is high (~5%). In this case, an effective cross-relaxation among 3F4, 3H4, and 3H6 manifolds produces almost two excited Tm ions at an upper laser level 3F4 for each pump quantum. However, the use of such high doped laser crystals is accompanied by such negative phenomena as an increase in the rate of excitation migration, upconversion losses and a high local dissipation of heat, causing a strong thermally induced lens [1]. In works [2–6] the authors realized diode-pumped Tm:YLF lasers by using active elements with Tm concentrations from 3% to 4% Tm and obtained slope efficiencies in the range 23–52%. The highest efficiency was obtained under special complicated pumping conditions, such as the use of two pump beams [2,3], or even four [4], or double-pass resonator cavity [5].

One of the promising ways to eliminate of aforementioned drawbacks is to use a pumping source with a wavelength near 1.7 μm corresponding to absorption by Tm ions on the transition 3H6-3F4. The pumping directly into the transition 3H6−3F4 for thulium lasers was realized in [7], where the authors investigated a Tm:KY(WO4)2 laser under laser-diode pumping at a wavelength of 1.75 μm. They used a 2 W InGaAs fiber-coupled diode laser. A maximum output power of 86 mW with a slope efficiency of 28% at 1950 nm was demonstrated. The efficiency observed experimentally was significantly lower than can possibly be expected for a thulium laser with such a type of pumping.

In the present work, we studied a Tm:YLF laser pumped into transition 3H6−3F4 by the Raman shifted Er-fiber laser (RSEFL) operated at 1678 nm. This pumping channel had been used successfully in our earlier experiments with a Tm:Ho:YLF laser [8], where 460 mW output power was obtained with a slope efficiency of 50%. These results are close to the results reported before in [9,10] where a Tm, Ho-codoped active element under Co:MgF2 laser pumping (λ = 1682 nm) demonstrated the best slope efficiency of ~59% at about 200 mW output power.

To the best of our knowledge, the advantages of 3F4 pumping for a Tm,Ho-doped laser were first described in a theoretical paper by Payne et al. in 1992 [11]. The results of our own experimental investigations and comparison of Tm:YLF laser characteristics for high ~5% and low ~1.5% (when effect of cross-relaxation is low) values of Tm3+ ion concentrations and for the RSEFL and 792-nm laser diode (LD) pumping sources form the subject of this paper.

2. Spectroscopy experiments

The Tm:YLF levels [12] are presented in Fig. 1. There are several transitions which are in the phonon assisted resonance with a pumping beam. Those transitions, which are marked by digit (2) in Fig. 1, can decrease the laser performance due to upconversion effect. The luminescence spectrum was analyzed to estimate the importance of the upconversion loss.
The polarized absorption spectra of 2 mm-thick sample were recorded by SHIMADZU UV-3600 spectrophotometer equipped with a Glan-Thompson prism. The crystal is cut so that its geometric axis is perpendicular to the crystallographic axis c. Unpolarized luminescence spectrum was recorded by using the MDR-204 monochromator (“LOMO-Photonics”, 300 mm focal length) under the illumination of an RSEFL (“ELR-3-1680PM”, IRE-Polyus, collimated output, M2<1.1, beam diameter ~1.5 mm). The absorption and luminescence spectra are shown in Fig. 2. Fig. 2 demonstrates that there is no noticeable luminescence in the visual range. The only strong 800-nm radiation from 3H4 manifold is radiated by the crystal. This manifold is populated by either the excited state absorption (ESA) on 3F4 manifold or the energy transfer upconversion (ETU) (3F4 + 3F4) → (3H6 + 3H4). The presence of this radiation in the laser cavity result in the effect of LD pumping is to some extent reproduced also for RSEFL pumping.

The absorption spectrum of an active element (AE) in medium IR-area is presented in Fig. 3 as well as pumping and lasing spectra. Although the lasing experiments are described in the next section the lasing spectrum is plotted here in order to estimate a value of the reabsorption loss in the unpumped region of the crystal.

3. Laser experiments

The laser scheme is shown in Fig. 4. We used either 5%-Tm doped sample with sizes of Ø8×2 mm or 1.5%-Tm doped sample of the same diameter and of 8 mm of length as the active element (4). The plane-parallel faces of the AE are not antireflection coated. The AEs are pumped by a single-mode RSEFL (1). The wavelength λ and a linewidth of the pump laser radiation are 1678 and 2.4 nm, respectively. The output power is varying within 3 W in experiments with a 5%-Tm doped sample and within 2 W with a 1.5%-Tm doped sample. The pump beam is focused into the AE by an 80 mm focal length lens (2). The beam was π-polarized (E||c).

The pumping at a wavelength of 792 nm was performed using a fiber-coupled diode array (LIMO); the numerical aperture, the fiber diameter, and the maximum cw output power were 0.22, 0.116 mm, and 10 W, respectively. The pump beam was focused on the AE by a 25 mm focal length objective (2).

Fig. 1. Tm:YLF levels. Transitions shown are: [1678] and [792] — pumping beams with wavelength shown in brackets; (1) — phonon assisted cross-relaxation; (2) — resonant and quasi-resonant ESA for 1678-nm pumping.

Fig. 2. Visible and near IR absorption and luminescence (under 1678-nm pumping) spectra of Tm:YLF crystal. Thick solid line — absorption of π-polarized light, thin solid line — absorption of σ-polarized light, dashed line — luminescence (in arbitrary units). Absorption spectra at wavelengths shorter than 580 nm are 10 times zoomed.

Fig. 3. The absorption spectrum of active element at medium IR-region, pumping (1) and lasing (2) spectra. Thick line — absorption of π-polarized light, thin line — absorption of σ-polarized light.

Fig. 4. Scheme of the experimental setup: (1) fiber-coupled pump laser; (2) focusing objective; (3) dichroic input mirror; (4) active element; (5) output coupler; (6) power meter; (7) MDR-204 monochromator.
The beam profile was tested in free space by a “90/10 knife-edge technique” for both pumping sources. For RSEFL beam the measured spot diameter and confocal length (which is twice the Rayleigh length) were $(80 \pm 8) \mu m$ and $(15 \pm 1.5) mm$ respectively. The waist diameter at $1/e^2$ level of power is 1.56 times greater than “90/10” spot diameter and is equal to $(125 \pm 12) \mu m$. The corresponding theoretical value of Rayleigh length is equal to $Z_R = \pi w_0^2/\lambda M^2 = (6 \pm 1.2) mm$. In the case of LD pumping the waist diameter and Rayleigh length were obtained in the similar way and yield $(230 \pm 40) \mu m$ and $(1.1 \pm 0.3) mm$ respectively.

The two-mirror laser cavity was formed by a plane mirror, high reflecting for $2 \mu m$ (3) (~90% transmission for either pumping beam) and an output coupler of $52 \mu m$ radius of curvature and 98% or 94% reflectivity (5). The distance between mirrors was varied from 11 to $52 \mu m$. The best results were obtained for 94% output coupler and $52 \mu m$ cavity length. The experimental setup includes power meter (“Ophir Nova2”) (6) and monochromator MDR-204 with PbS infrared sensor (7).

![Fig. 5. Output power vs. absorbed pump power diagram for different lasing conditions.](image1)

The dependencies of output power on absorbed pump power for different active elements, different pump sources and for pulsed or CW pumping regimes are presented in Fig. 5. All experimental data were measured with 15% errors caused by optical non-uniformity of AE, the influence of environment humidity and power meter stability.

The highest values for the total and slope efficiencies of RSEFL pumped Tm:YLF laser at 1.5%-Tm ion concentrations reached in our experiments were ~45% and ~50% respectively at an output power ~320 mW. It is thus demonstrated experimentally that even with low Tm-ion concentrations a Tm:YLF laser can have high efficiency. The independence of laser efficiency on Tm ion concentrations allow the use of a long, weakly-doped active element which can reduce thermal loading and improve output laser characteristics. The reasons why the slope efficiency is still far away from the theoretically possible ones are both the upconversion losses via $^4H_4$ level and the intracavity losses, which are caused by the uncoated surfaces of the crystal.

In contrast, a dramatic reduction of laser efficiency for 1.5%-Tm doped active element was observed for LD pumping (Fig. 5). The total and slope efficiencies were only ~2.5% and 3.3% respectively. Such low laser efficiency is explained by two reasons: first, the low value of cross relaxation effect and secondly, a short Rayleigh length due to higher pumping beam divergence and shorter focal length of focusing lens. Laser efficiency was significantly higher for 5%-Tm ion concentrations. The total and slope efficiencies were increased up to 23% and 27% respectively. It shall be mentioned that the confocal length in the case of LD pumping was ~3 mm instead of more than 15 mm for RSEFL (in the YLF crystal the index of refraction is equal to 1.45). For this reason, due to the pumping and the lasing modes’ mismatch, the lasing efficiency for LD pumping is significantly less than that for the RSEFL case.

The typical lasing spectrum is presented in Fig. 3. It consists of two or three narrow lines (0.7 nm FWHM) with the wavelengths from 1.91 to 1.93 $\mu m$. The wavelength determination accuracy is about 2 nm. Most probably the line form of spectrum is defined by a spurious Fabry–Perot etalon, which is formed by the uncoated face of AE and a flat cavity mirror.

Temporal behavior of RSEFL pumped Tm:YLF laser output radiation is typical for all Tm-doped crystals. The trace of a laser pulse is shown in Fig. 6 where the signal was recorded by means of a Hamamatsu G5852 photodiode without optical filtering, and the pumping beam was overlapped by the laser beam. The pulse was formed by a chopper placed in the pumping channel. The pulses in Fig. 6 have different duration due to unstable rotation speed of the chopper. In the pulse structure, one can clearly observe a stage of rapid signal increase during the opening of the chopper, followed by a
stage of slow signal increase during the formation of population inversion. This slow increase is caused by saturation of the absorption as well as increasing luminescence. After this, lasing starts and spikes of emission are observed on the pumping beam background. The reason for the spiked structure of the beam intensity is relaxation oscillations which are not dumped in the case of Tm-laser because its upper-state lifetime is relatively long. The trace in the inset (Fig. 6(b)) is recorded with the better time resolution. The origin of the time scale is shifted to the first spike of lasing. The experimental conditions for this trace are the same as for the lower trace in Fig. 6(a). The measured period $T$ of spikes is equal to $\sim 21 \mu$s which is in qualitative agreement with the theoretical value [13]:

$$T = \frac{2\pi}{\sqrt{\left(P_{\text{abs}} / P_{\text{th}} - 1\right)}} / t_c \tau,$$

where: $P_{\text{abs}}$ is the absorbed pump power, $P_{\text{th}}$ is the threshold absorbed pump power, $t_c$ is the cavity decay time and $\tau$ is the lifetime of ions in the upper laser level.

The cavity decay time is equal to:

$$t_c = \frac{L_{\text{res}}}{c \ln(R_{\text{oc}})},$$

where: $L_{\text{res}}$ is the length of the laser cavity, $c$ is the speed of the light, and $R_{\text{oc}}$ is the reflectivity of the output coupler.

The calculated value of $T$ is equal to $\sim 29 \mu$s for experimental conditions corresponding to the trace presented in Fig. 6(b): $P_{\text{abs}} / P_{\text{th}} = 2.3$, $L_{\text{res}} = 52$ mm, $R_{\text{oc}} = 0.94$, and $\tau = 9.5$ ms.

An interesting feature of the recorded pulse is a peak of lasing when a chopper starts closing the pumping beam (the falling edge of a pulse). We attribute this peak to a decrease of the upconversion loss, which is caused by ESA from $3F_4$ level. The falling edge of the pump beam is indicated in Fig. 6(a) by the dashed line.

The diameter of a focal spot for an identical output laser power was measured in order to confirm our expectation of better beam quality for low Tm doped crystals. The results are presented in Fig. 7. The parameters of testing were the following: $\sim 6$ cm focal length lens was placed $20$ cm apart from the output coupler. The Ge-plate was placed in front of the lens to cut-off pumping beam. An InGaAs photodiode was placed after a low-speed chopper (one pair of blades, rotation speed $-2$ s$^{-1}$) and was illuminated through diffused sandglass, placed between chopper and photodiode.

The beam propagation factor $M^2$ confirms the predicted behavior. Namely, the best value ($M^2 = 3.4$) was obtained for the sample with the doping of 1.5% under RSEFL pumping. The poorest value ($M^2 = 5.7$) was obtained for 5%-Tm doping and also under RSEFL pumping because under these conditions the strongest thermal lens was formed. Almost the same value of $M^2$ ($M^2 = 5.2$) was obtained for 5%-Tm doping sample under LD pumping. For comparison, the authors of work [3] reported the value of 2.5 for $M^2$. They used two beams pumping by the pitsigaled diode arrays of 40 W each. The calculated pumping power density was equal to 8 kW/cm$^2$ assuming the “flat-top” power distribution. In our experiments the pumping beam waist was much smaller ($0.12$ mm in diameter) and due to Gaussian profile of the beam the power density in the spot center is twice as large compared to a flat-top power distribution. For the above mentioned reasons the absorbed power density is as high as $-13$ kW/cm$^2$ even for the moderate pumping of 0.7 W absorbed power. Very tight focusing caused relatively bad beam propagation factor.

4. Conclusions

For the first time the $^{3}H_6 \rightarrow ^{3}F_4$ pumping channel has been realized for a Tm:YLF laser and lasing performance of two types of pumping has been compared. The lasing in a low concentration Tm-doped YLF crystal was obtained with the slope efficiency of $\sim 50\%$ relative to the absorbed power. The beam propagation factor was measured for both pumping channels and two concentrations of Tm. The theoretical prediction that this pumping channel can be advantageous is confirmed. The result of our investigations and the appearance last year of new commercially available [14] high-power laser diodes emitting in the 1.6–1.8 µm region opens new perspectives in the development of 2 µm thulium-doped lasers.

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