Low threshold Nd^{3+}:$KY(WO_4)_2$ laser operated at 1072 nm pumped by diode

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The diode-pumped Nd:KYW laser operated in the free-running mode at 1072 nm is demonstrated at room temperature. The laser output power of 102.6 mW with 12.07% optical-to-optical conversion efficiency and 13.16% slope efficiency is obtained. The laser threshold is about 110 mW. Such a low threshold is in agreement with the theoretical prediction.

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In recent years, tungstate as a laser host material has attracted considerable attention due to its excellent physicochemical property. Rare-earth-doped double tungstates, for instance, $KGd(WO_4)_2$ (KGW), $KY(WO_4)_2$ (KYW), $NaY(WO_4)_2$ (NaYW) and so on, have been reported[1−6]. In these compounds, the Nd^{3+}-doped $KGd(WO_4)_2$ and $KY(WO_4)_2$ crystals have been gradually better developed, because of their many advantages, such as low excitation threshold, high output energy and high efficiency, stronger Raman scattering, and so on[3,5,7]. On the other hand, high Nd^{3+} doping concentration in these crystals has both weaker fluorescence quenching effect and broader and stronger absorption band at around 808 nm[2,5]. With these advantages, Nd:KGW and Nd:KYW crystals play an important role in the domain of stimulated Raman scattering self-frequency conversion and laser, because Raman and laser properties can be combined simultaneously. Recently, some researches of flash-lamp or diode-pumped Nd:KGW in both free-runnig and passively Q-switched modes have been reported[7−11], but little attention was paid to diode-pumped Nd:KYW crystal. In this letter, the diode-pumped Nd:KYW laser was demonstrated in free-running mode at room temperature. The lower threshold is in agreement with the theoretical prediction.

The absorption spectrum and near infrared luminescence spectrum of Nd:KYW are shown in Figs. 1 and 2, respectively. The absorption spectrum includes nine main absorption bands in the range from 300 to 1000 nm, which correspond to transitions from the ground state $^4I_{9/2}$ to the excited states. One of these intense absorption bands at around 810 nm is observed to fit 808-nm diode pumping. Its full-width at half-maximum (FWHM) is 10 nm and its absorption cross-section is 5.02×10^{-20} cm^2. The luminescence spectrum was recorded in the infrared spectral range from 850 to 1450 nm at room temperature. There are three main emission bands at 916, 1072, and 1355 nm, corresponding to the $^4F_{3/2} \rightarrow {}^4I_{J'}$ ($J' = 9/2, 11/2, 13/2$) transitions of the Nd^{3+}, respectively. Generally, the three luminescence spectral lines are very important in laser application area, especially at 1072 nm. The stimulated emission cross-section (σ_{em}) for the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition is 32.41×10^{-20} cm^2.

The fluorescence lifetime curve is shown in Fig. 3. The fluorescence lifetime τ_{f} of the $^4F_{3/2}$ level of Nd:KYW was obtained to be about 80.3 μs. The factor $\sigma_{\text{em}} \times \tau_{\text{r}}$ sometimes is used to predict the laser threshold of crystal. According to Payne's theoretical calculation[12], the relationships among the laser threshold, the pump spot size, and the factor $\sigma_{\text{em}} \times \tau_{\text{r}}$ are shown in Fig. 4. For given optimum size of the pump beam and laser resonator, the laser threshold is in inverse proportion to the factor

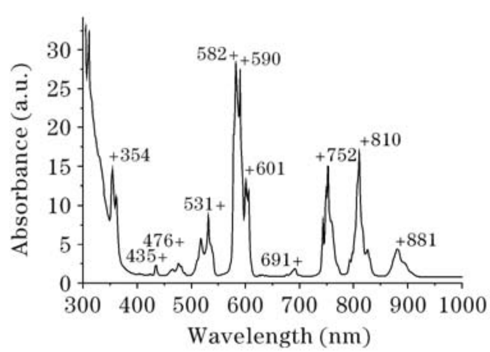

Fig. 1. Absorption spectrum of Nd^{3+}:KYW crystal.

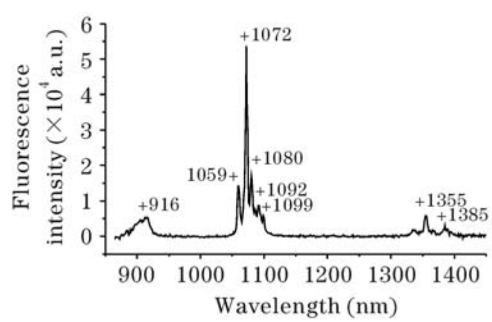

Fig. 2. Luminescence spectrum of Nd^{3+}-doped KYW crystal at room temperature.

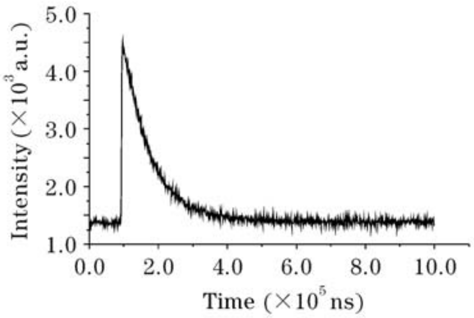

Fig. 3. Fluorescence lifetime of the Nd:KYW crystal.

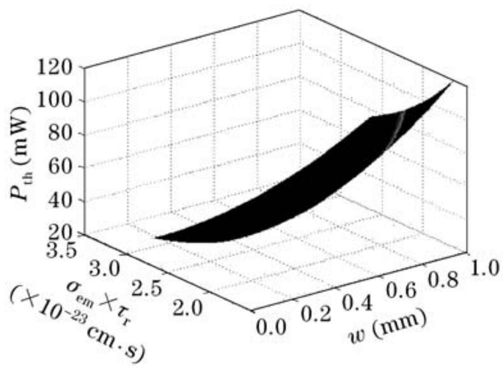

Fig. 4. Laser threshold P_{th} as function of the pump beam size w and the factor $\sigma_{em} \times \tau_r$.

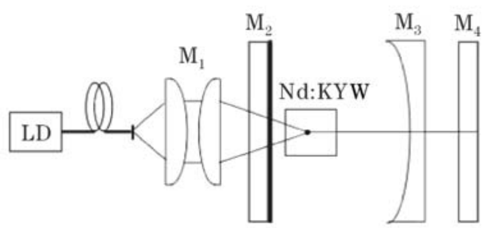

Fig. 5. Schematic of Nd:KYW laser resonator.

$\sigma_{em} \times \tau_r$. For our crystal, the larger $\sigma_{em} \times \tau_r$ (26.18×10^{-24} cm·s) suggests that Nd:KYW maybe have a lower threshold compared with many other laser crystals.

The experimental setup is shown in Fig. 5. The length of resonant cavity was chosen to be about 7 cm. It consisted of coupling system M_1, input flat mirror M_2, output concave mirror M_3 with curvature radius of 150 mm, and a long wave pass color filter M_4. M_2 with high transmission coating at 810 nm ($T = 99.9\%$) and high reflectivity coating at 1.072 μm was deposited slightly close to the input end of the crystal. Output mirror M_3 with reflectivity coating at 1.072 μm ($R = 97.49\%$ or 92.66%) and high reflectivity coating at 810 nm was placed in front of the other end of the crystal. Both end faces of the crystal along the crystallographic axis were coated anti-reflectivity at 1.072 μm. The propagation length of the Nd:KYW which was pumped longitudinally was 3 mm. Fiber output was focused into the Nd:KYW crystal by coupling system M_1 and the pump spot size was about 0.80 mm. In order to enhance the stability of laser output power and the matched degree between the spectral width of laser diode (LD) and absorbed spectrum of Nd:KYW crystal at 810 nm, the temperature of LD was controlled by a thermoelectric cooler, whose hot end was simultaneously cooled by self-circulated cooling water. As a result, the temperature of LD was tuned to 25 °C with fluctuation less than ±0.15 °C, and the LD maximal wavelength was about 809 nm.

Figure 6 shows the relationship between the laser output power and the input pump power. For the output coupler $R = 92.66\%$, the output power is higher than that of $R = 97.49\%$. For $R = 92.66\%$, laser output power of 102.6 mW with laser emission ($^4F_{3/2} \rightarrow 4I_{11/2}$ transition) peaking at 1072 nm has been realized in the free-running mode, when the pump power was 850 mW. The optical-to-optical conversion efficiency and slope efficiency were about 12.07% and 13.16%, respectively. The laser threshold power was about 110 mW in the experiment. The lower threshold is in accordance with the prediction of the above theoretical analysis. According to Payne theoretical calculation[12], Fig. 7 illustrates the slope efficiency as function of the resonator loss factor and the conversion efficiency. From Fig. 7, both low pumping conversion efficiency and low slope efficiency prove that the loss is very high in our resonator. According to the standard $ABCD$ ray propagation matrix, the spot size of the fundamental transverse mode is about 0.16 mm in the center of the laser crystal. Generally, an optimum mode matching ($\omega_p \approx \omega_0$) between fundamental transverse mode of the resonator cavity and the pumping mode must be met. According to Fig. 4, the pumping spot size disagrees with the spot of fundamental transverse mode of optical cavity. The optimum mode is mismatched between the pumping mode and fundamental transverse mode. The laser may

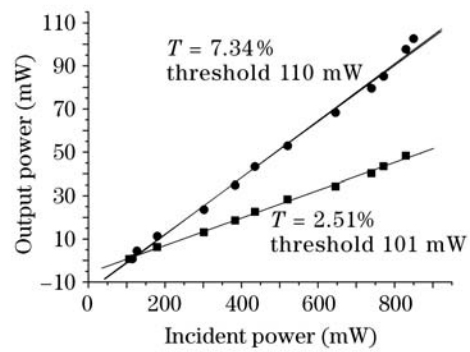

Fig. 6. Laser output power of Nd:KYW crystal at 1072 nm versus LD pumping power in the free-running mode.

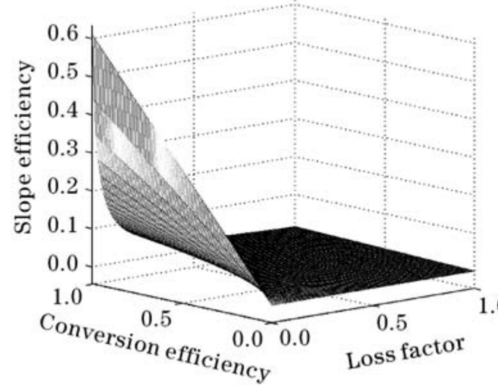

Fig. 7. Relationship among the slope efficiency, the conversion efficiency, and the loss factor.

operate with multi-transverse mode. The loss increased. According to Fig. 7, it makes both the pump power utilizable efficiency and slope efficiency reduce synchronously. Moreover, there is an important reason that the pumping wavelength slightly disagreed with the absorption wavelength at 810 nm. At last, the transmission of the output mirror has an effect on the output power. The transmission is bidirectional, namely, there is an optimal transmission for higher output power. Maybe $T = 7.34\%$ is not the optimal transmission in our experiment. Avoiding the above causations, we believe that preferable result would be achieved.

Based on the above analysis, the lower threshold of Nd:KYW crystal is due to larger stimulated emission cross-section and longer lifetime mainly. Compared with the Nd:KGW crystal reported in Ref. [9] ($C_{\mathrm{Nd}^{3+}} = 5$ at.-%, $P_{\mathrm{th}} \approx 200$ mW), the Nd:KYW has about one half as great a threshold as Nd:KGW, so the Nd:KYW crystal is easier to realize high power micro-laser than the Nd:KGW crystal. In comparison with the Nd:NaYW crystal reported in Ref. [13], the threshold and the optical-to-optical conversion efficiency are much lower. Such low efficiency operation is not surprising. We are considering the enhancement of laser efficiency in our next work.

In summary, diode-pumped laser with 12.07% optical-to-optical conversion efficiency and 13.16% slope efficiency, which operated in the free-running mode at 1072 nm, was demonstrated at room temperature, when the pump power was 850 mW. The laser threshold was about 110 mW. Such low threshold proves that the experimental result accords with the theoretical analysis. Moreover, the low efficiency causations were analyzed. In a word, Nd:KYW crystal has the potential as a compact and high-efficiency diode-pumped solid-state micro-laser material in future.

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