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Continuous-wave diode-pumped Yb:glass laser with near 90% slope efficiency

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Room temperature highly efficient laser action from an ytterbium-doped phosphate glass is demonstrated when end pumped by a 975 nm fiber-coupled laser diode. Laser slope efficiencies as high as 88% have been obtained, leading to pump-to-laser conversion efficiencies greater than 50%. From the analysis of pumping threshold and laser slope efficiencies the authors have determined both the optical losses and emission cross section at laser wavelength (1028 nm). © *2006 American Institute of Physics*. [DOI: 10.1063/1.2345828]

There is presently a great interest in ytterbium lasers because of the increasing ability of high power high brightness InGaAs laser diodes emitting near 980 nm. The simple energy level diagram of ytterbium ions prevents some processes, such as up conversion and excited state absorption, which could lead to drastic reductions in the laser slope efficiency as well as to noticeable increments in the laser thermal loading.[1,2] The absence of cross relaxation permits high dopant concentrations while maintaining low fluorescence quenching. Due to the typically high fluorescence quantum efficiency of the $^2F_{5/2}$ metastable state (usually above 0.9) and to the very low quantum defect (typically below 10%), Yb^{3+} lasers exhibit low pump-induced thermal loading.[3] Nevertheless, under moderate or high pump intensities, the effects of pump-induced thermal loading cannot be neglected even in Yb^{3+} lasers. As for example, pump-induced local heating at the pumping volume causes depolarization and ground state depopulation.[4] Additionally, pump-induced thermal lensing could lead to spatial deformation of intracavity beams reducing the pump and laser beam overlap and, consequently, the laser slope efficiency.[4,5] Thus, in order to achieve highly efficient Yb^{3+} lasers, the research is focusing much attention on laser hosts with superior thermal and thermo-optic properties.

Ytterbium-doped glass materials are especially interesting because they are significantly cheaper than crystals and they have a smoother fluorescence spectrum, making them interesting for generation of ultrashort pulses and tunable laser sources.[6] In particular, QX laser glasses have demonstrated a significant enhancement in thermal loading capabilities over other conventional phosphate glasses.[7] In fact, multiwatt output powers have been already obtained from Nd^{3+} and Er^{3+} doped QX glass lasers operating at 1054 and 1540 nm, respectively.[8,9] In addition to its superior thermomechanical properties QX glass materials also show excellent thermo-optical properties.[7,10] They exhibit an almost vanishing thermal coefficient of optical path length ($ds/dT \approx 2.1 \times 10^{-6}\ \mathrm{K}^{-1}$ as obtained by thermal lens spectroscopy),[10] mainly due to its close to zero temperature coefficient of refractive index ($dn/dT \approx -0.2 \times 10^{-6}\ \mathrm{K}^{-1}$) and low thermal expansion coefficient ($8.3 \times 10^{-6}\ \mathrm{K}^{-1}$).[7] This fact, in addition to the good spectral properties of Yb^{3+} ions in QX glass host (such as long lifetime, high absorption cross section, and large emission bandwidth),[6,7,10] makes ytterbium-doped QX phosphate glasses (hereafter QX/Yb) a promising candidate for highly efficient laser operation. Continuous-wave laser action from QX/Yb has been already demonstrated under Ti:sapphire and diode pumping.[11,12] Nevertheless, in both cases the reported laser slope efficiencies, with respect to the absorbed pump power, were not larger than 50% and the maximum output powers were restricted to 500 mW. In this sense the potential ability of the QX/Yb system for highly efficient near infrared laser light generation is still left to be demonstrated.

This letter reports on stable and highly efficient continuous-wave laser operation in a QX/Yb glass under diode pumping. Emission cross section and optical losses have been estimated from the analysis of the laser slope efficiencies (η_L) and pump power at threshold (P_{th}). It has been demonstrated that for the optimum pumping conditions and output coupler transmittance, laser slope efficiencies in excess of 85% can be obtained.

As a gain material we have used a 6.8 wt. % Yb_2O_3 doped Kigre QX phosphate glass. Initially the QX/Yb was a sample with $3 \times 5 \times 3\ \mathrm{mm}^3$. The fluorescence lifetime was measured to be 2 ms. End pumping was performed by a 50 μm fiber-coupled 2 W laser diode (Unique-Mode VDM 38) tuned to $\lambda_p = 975$ nm. The fiber output was first collimated by an OFC collimator and then focused by a single 3 cm focal lens. After the focusing lens, the pumping mode radius ω_p and the M^2 factor were measured to be 45 μm and 10, respectively. When focused into a QX/Yb glass with a refractive index of $n \approx 1.5$, the confocal length of the pump beam, $l_{\mathrm{cp}} = 2n\pi\omega_p^2/M^2\lambda_p$,[13] is estimated to be 2 mm. We have used this value as a guide to determine the optimum length of our QX/Yb gain medium. Since in Yb^{3+} end-pumped lasers, optimum mode matching is achieved when the confocal length of the pump is equal to or longer than the crystal length,[13] we have reduced the QX/Yb thickness down to 2 mm. The gain medium, which was not actively cooled, was placed inside a double-pass plane-concave cavity consisting of a flat input mirror and a 10 cm radius of curvature

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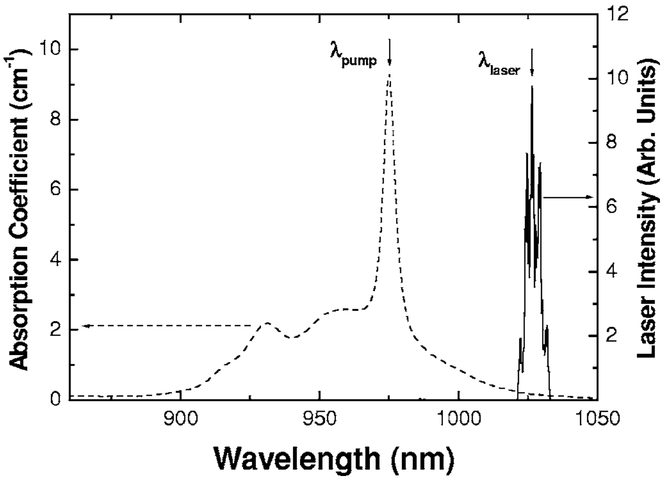

FIG. 1. Room temperature absorption spectrum of our 6.8 wt % doped QX glass (dashed line). The solid line is the laser spectrum corresponding to the diode-pumped QX/Yb laser operating in a free-running mode.

output coupler. The flat dichroic input mirror was of 99.9% and 10% reflectance at 1.02 and 0.98 μm, respectively. The output coupler transmittance was varied from 0.3% up to 10% by using different output mirrors; all of them were also of high reflectance (>90%) at the pump wavelength. The QX/Yb sample was placed close to the input mirror, where the laser beam waist is located. The faces of the QX/Yb sample were not antireflection coated. The distance between the input mirror and the output coupler was set to 9.9 cm, leading to a laser beam waist ω_l of about 56 μm, so that $a=\omega_p/\omega_l\approx 0.8 \leqslant 1$, as it is required for optimum pump and laser mode overlap.[5]

Under these experimental conditions stable and TEM$_{00}$ laser light generation was achieved with all the couplers used. The spectral distribution of laser radiation has been measured by using a 0.05 nm resolution fiber-coupled spectrometer (Ocean Optics HR4000). The free-running laser spectrum, which was found to be almost independent of the output mirror transmittance and pump power, is shown in Fig. 1. From this we have obtained an average free-running laser wavelength of $\lambda_l=1028$ nm, leading to a quantum defect between pump and laser radiations as low as 5%. This reduced quantum defect is an outstanding feature for highly efficient operation since the maximum laser slope efficiency is proportional to the ratio between pump and laser wavelengths ($\eta_l \propto \lambda_p/\lambda_l$),[5] and also because a reduced quantum defect ensures a minimized pump-induced thermal loading in the gain medium.

Figure 2 shows the laser slope efficiency (measured with respect to the absorbed pump power) as a function of the output mirror transmittance. For an end-pumped solid-state laser in absence of excited state absorption and for similar laser and pump beam waists, the laser slope efficiency η_{laser} can be written as[5]

$$\eta_{\text{laser}} = \frac{\lambda_p}{\lambda_l}\frac{T'}{T'+L}, \tag{1}$$

where λ_p and λ_l are the pump and laser wavelengths, L is the round-trip loss, and T' is the effective transmittance, which takes into account the reflection factors owing to the absence of antireflection coatings in the surfaces of our QX/Yb sample. The effective transmittance can be written as[14]

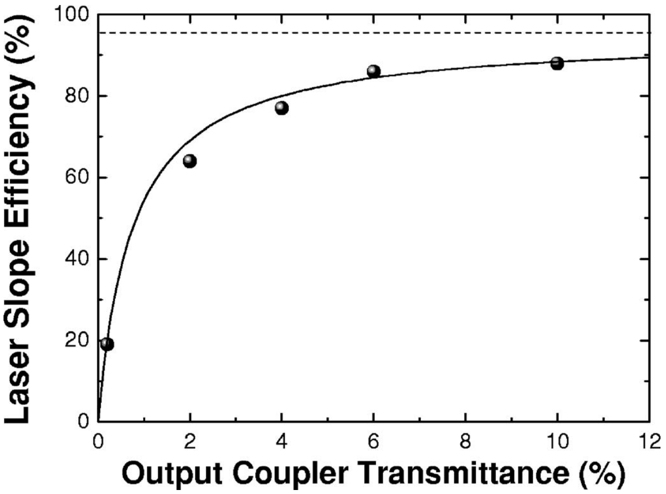

FIG. 2. Laser slope efficiency as a function of the output coupler transmittance as obtained for a diode-pumped QX/Yb laser. The solid line is the best fit to expression (1). The dashed line is the theoretical maximum slope efficiency achieved in a 975 nm pumped QX/Yb laser operating at 1028 nm.

$$T' = 1 - \left[\frac{(\sqrt{r}+\sqrt{1-T})^2}{(1+\sqrt{rT})^2}\right], \tag{2}$$

with $r=(n-1)^2/(n+1)^2$ (i.e., the reflectivity of the QX/Yb faces), $n=1.55$ is the QX/Yb refractive index, and T is the output coupler transmittance. We have included, as a solid line in Fig. 2, the best fit of experimental data to expressions (1) by taking into account the relation between output coupler transmittance and the effective transmittance [expression (2)]. From this fit we have obtained a round-trip loss of $L=0.005$. This leads to a loss factor for QX/Yb lasers of 0.012 cm^{-1}. This value is, in fact, lower than those previously reported for other efficient Yb^{3+} lasers such as Yb:LiNbO$_3$ crystals[15] and is comparable to those values reported for other solid-state laser materials.[5]

From Fig. 2 the maximum slope efficiency is obtained when the $T=6\%$ output coupler was used. Figure 3 shows the 1.028 μm laser power versus the absorbed pump power for this output coupler transmittance. The dots are experi-

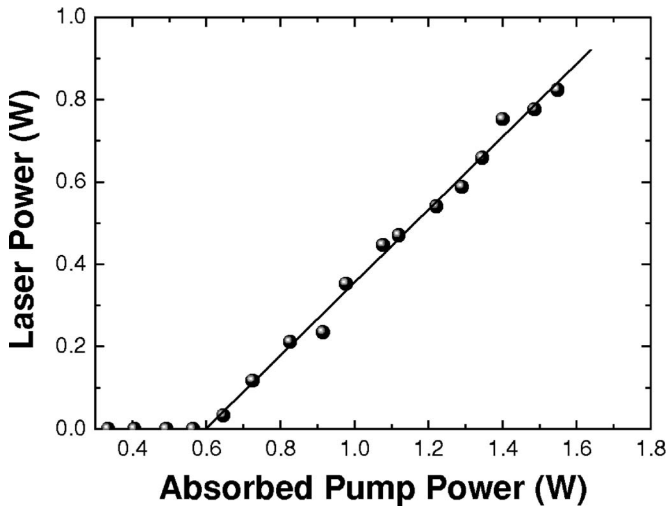

FIG. 3. Output laser power as a function of absorbed pump power. The output mirror transmittance was 6%. The dots are experimental data and the solid line is best fit to a linear relation. The dashed line is the theoretical maximum slope efficiency.

mental data and the solid line is the best fit to a linear behavior. For all the pump powers the output laser beam was found to oscillate in a TEM_{00} Gaussian mode. From the linear fit shown in Fig. 3 we have obtained a laser slope efficiency as high as 88%. This is among the highest slope efficiencies reported for a diode-pumped Yb^{3+} laser operating at room temperature. It is, in fact, comparable to that obtained from a cryogenically cooled diode-pumped ytterbium-doped yttrium aluminum garnet laser (85% of slope efficiency)[16] and at room temperature to Ti:sapphire pumped $\text{Y}_3\text{ScAl}_4\text{O}_{12}$ ceramic or Ti:sapphire pumped $\text{Sr}_5(\text{PO}_4)_3\text{F}$ crystal (in both cases the slope efficiency was 72% with respect to the input pump power).[17,18] We achieved a maximum output power of 0.82 W at 1028 nm. To date, this is the highest continuous-wave output power from a QX/Yb glass laser of which we are aware. The maximum absorbed pump power was 1.55 W, corresponding to an incident pump power of 2 W. This results in a high optical-to-optical efficiency of 40%, which corresponds to an efficiency of 53% with respect to the absorbed pump power. Both conversion efficiencies and output powers here reported under diode pumping constitute a clear improvement with respect to previous data concerning Ti:sapphire and diode-pumped QX/Yb glasses providing optical-to-optical conversion efficiencies not greater than 30% and 22%, respectively.[11,12]

The absorbed pump power at threshold has been also determined from the linear fit shown in Fig. 3 being 600 mW. In a quasi-three-level laser system, the absorbed pump power at threshold is given by[5]

$$P_{\text{th}} = \frac{\pi h \nu_p (\overline{\omega_l^2} + \overline{\omega_p^2})(T + L + 2L_{\text{Yb}})}{4\sigma_{\text{em}}\tau_F}, \tag{3}$$

where ν_p is the pump frequency, ω_p and ω_l the pump and laser beam waists, respectively, $\tau_F = 2$ ms the fluorescence lifetime, $T = 0.06$ the output mirror transmittance, $L = 0.005$ the round-trip loss, and L_{Yb} the one-pass reabsorption loss in the glass at laser wavelength. From the absorption spectrum we have estimated $\alpha_{\text{abs}}(1028\ \text{nm}) = 0.135\ \text{cm}^{-1}$ so that $L_{\text{Yb}} = 1 - e^{-\alpha_{\text{abs}}\ \text{crystal}} \approx 0.027$. Including all these data in expression (3) we have obtained $\sigma_{\text{em}} \approx 0.82 \times 10^{-21}\ \text{cm}^2$. This value is in agreement with those obtained from luminescence experiments, $\sigma_{\text{em}} \approx 1.2 \times 10^{-21}\ \text{cm}^2$.[6]

In summary we have demonstrated the efficient operation of a diode-pumped ytterbium-doped QX glass laser. For optimum sample dimensions, output coupler transmittance, and pump and laser beam waists inside the gain medium, laser slope efficiencies as high as 88% have been obtained. We state that the superior laser performance here reported arises from the low intracavity thermal loading as well as from the excellent thermo-optical properties of QX glasses. Better optical conversion efficiencies are expected by using antireflection coatings on the glass as well as by increasing the absorption coefficient at pump wavelength. The results obtained in this work make ytterbium-doped QX glasses a promising material for efficient diode-pumped multiwatt laser light generation in the infrared.

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