

**Continuous wave diode pumped Yb:glass laser with 90 % slope
efficiency.**

D. Jaque and J.C Lazeomacini

*GIEL, Departamento de Física de Materiales, Universidad Autónoma de Madrid, 28049,
Madrid, Spain.*

C. Jacinto and T. Catunda

*Instituto de Física de São Carlos, Universidade de São Paulo – USP,
CEP 13560-970, São Carlos – SP, Brazil*

(10 March 2006)

Room temperature highly efficient laser action from an Ytterbium doped QX phosphate glass is demonstrated when end-pumped by a 975 nm fiber coupled laser diode. Laser slope efficiencies as high as 90 % have been obtained, leading to pump-to-laser conversion efficiencies over to 50 %. From the analysis of pumping threshold and laser slope efficiencies we have determined both the optical losses and emission cross section at laser wavelength (1028 nm).

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 fact that there are only two electronic multiplets makes them suitable for highly efficient laser light generation around 1 μm . This simple energy level diagram 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 and large fluorescence lifetimes, ensuring then, high energy storage capabilities and relatively low thresholds. 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 suffer from a low pump induced thermal loading, especially when comparing to Nd^{3+} lasers.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 higher re-absorption losses, therefore leading to higher laser thresholds. 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 on laser hosts showing superior thermal and thermo-optic properties is focusing much attention⁶.

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^{2,4}. In particular, QX laser glasses have demonstrated a significant enhancement in

thermal loading capabilities over other conventional phosphate glasses.^{6,7} As a matter of fact, above 500 W/inch have been reported for rare earth doped QX glasses allowing for laser operation under high pump powers.² For instance, multi-watt output powers have been already obtained from Nd³⁺ and Er³⁺ doped QX glass lasers operating at 1054 and 1540 nm, respectively.² In addition to its superior thermo-mechanical properties QX glass materials also show excellent thermo-optical properties.³ They exhibit an almost vanishing thermal coefficient of optical path length, $ds/dT \approx 2.1 \cdot 10^{-6} \text{ K}^{-1}$, mainly due to its close to zero temperature coefficient of refractive index ($dn/dT \approx -0.2 \cdot 10^{-6} \text{ K}^{-1}$) and low thermal expansion coefficient ($8.3 \cdot 10^{-6} \text{ K}^{-1}$).^{3,7} Consequently, in rare earth doped QX glass lasers the undesirable effects of pump induced intracavity thermal lensing are minimized. This fact, in addition to the good spectral properties of Yb³⁺ ions in QX glass host (such as long lifetime, high absorption cross section and large emission bandwidth),^{2,3} 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.² 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.^{2,4} 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 high efficient laser 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 thresholds (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.% Yb₂O₃ doped Kigre QX phosphate glass. Initially the QX/Yb was a sample with 3x5x3 mm³. Absorption coefficient at 975 nm and fluorescence lifetime were measured to be 4 cm⁻¹ and 2 ms, respectively. 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, $l_{cp} = 2n\pi\omega_p^2/M^2\lambda_p$, 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 Yb³⁺ end-pumped lasers, optimum mode matching is achieved when the confocal length of the pump is equal or longer than the crystal length, we have reduced the QX/Yb thickness down to 2 mm. In this way we have obtained a 2x5x3 mm³ parallelepiped with the two 5x3 mm² faces polished up to optical grade. 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 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 input mirror and output coupler was set to 9.9 cm, leading to a

laser beam waist, ω_l , of about 56 μm , so that $a = \omega_p/\omega_l \approx 0.8 \leq 1$, as it is required for optimum pump and laser mode overlap.

Under these experimental conditions stable and TEM₀₀ 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 on the output mirror transmittance and pump power, is shown in Figure 1. From this we have obtained an averaged free-running laser wavelength of $\lambda_l = 1026$ 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 wavelength ($\eta_l \propto \lambda_p/\lambda_l$) 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 in absence of excited state absorption and for similar laser and pump beam waists, the laser slope efficiency, η_{laser} , can be written as:

$$\eta_{laser} = \frac{\lambda_p}{\lambda_l} \cdot \frac{T'}{T'+L} \quad (1)$$

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:

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

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 $L = 0.006$. This leads to a loss factor for QX/Yb lasers of 0.001 cm^{-1} . This value is in fact lower than those previously reported for other efficient Yb^{3+} lasers such as Yb:LiNbO_3 crystals [ref] and is comparable to those values reported for other solid state laser materials [ref].

From Fig. 2 the maximum slope efficiency is obtained when the $T = 6 \%$ output coupler was used. Due to the saturation in the laser slope efficiency further enhancement for higher transmittances is not expected. Figure 3 shows the $1.028 \mu\text{m}$ laser power versus the absorbed pump power for this output coupler transmittance. Dots are experimental 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 90 %. This is, up to the best of our knowledge, the highest slope efficiency ever reported for a diode pumped Yb³⁺ laser operating at room temperature. Furthermore it is comparable to that obtained from a cryogenically cooled diode pumped Yb:YAG laser (85 % of slope efficiency)⁵ and at room temperature Ti:sapphire pumped Y₃ScAl₄O₁₂ ceramic (72% with respect to the input pump power)⁸. We achieved a maximum output power of 0.8 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 was 1.47 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 55 % with respect to the absorbed pump power. Both conversion efficiencies and output power here reported under diode pumped 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^{2,4} [refs.].

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:

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

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, $T = 0.1$ the output mirror transmittance, $L = 0.006$ the round trip loss and L_{Yb} the one-pass re-absorption loss in

the glass at laser wavelength. From the absorption spectrum we have estimated $\alpha_{abs}(928\text{ nm}) = 0.12\text{ cm}^{-1}$ so that $L_{Yb} \approx 0.027$. Including all these data in expression (3) we have obtained $\sigma_{em} \approx 0.29 \cdot 10^{-19}\text{ cm}^2$. This value is in agreement with those obtained from luminescence experiments. ⁷ [ref].

In summary we have demonstrated the efficient operation of a diode pumped Ytterbium doped QX glass. For optimum sample dimensions, output coupler transmittance and pump and laser beam waists inside the gain medium, laser slope efficiencies as high as 90 % 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 multi watt laser light generation in the infrared.

This work has been supported by the Comunidad Autonoma de Madrid (Projects No. 07N/0020/2002 and No. GR/MAT/0110/2004), by Spanish Ministerio de Educacion y Ciencia (MAT2004-03347). C. Jacinto and T. Catunda would like to thank to the Brazilian agency FAPESP and CNPq for financial support of this work and to M. Myers and J. Myers from Kigre Inc. for providing the sample.

References

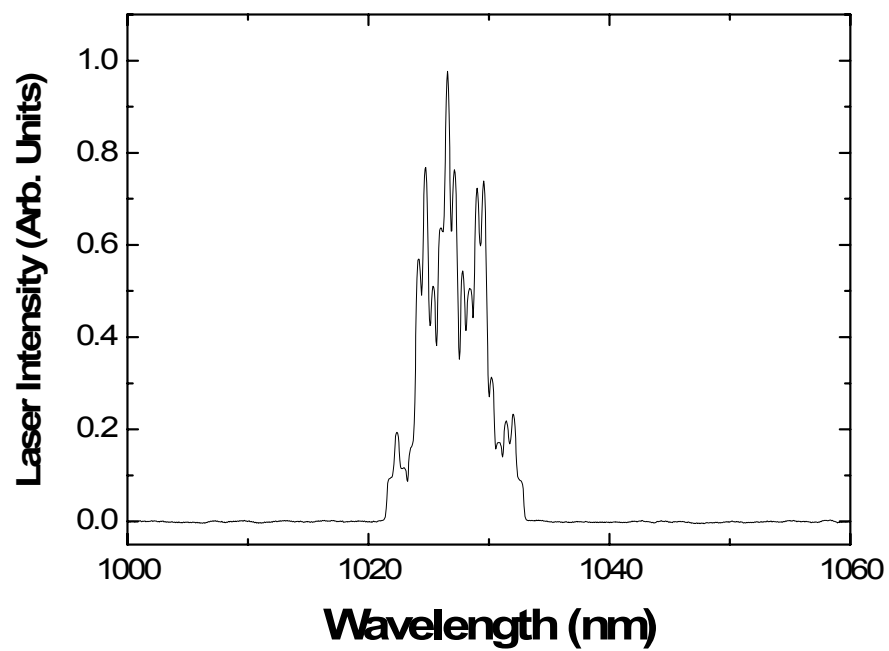
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Figure Captions

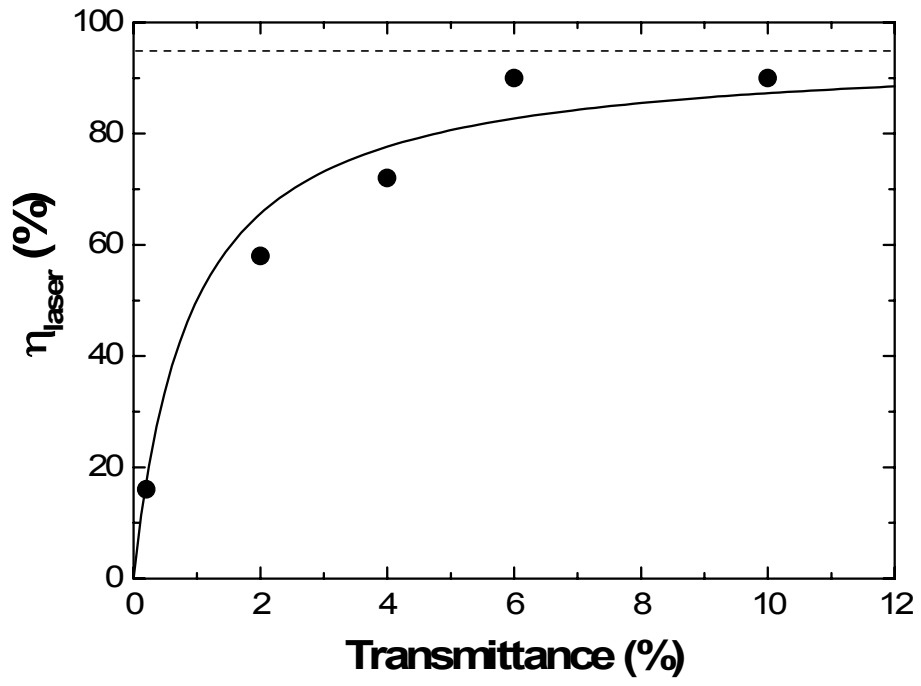
Figure 1.- Laser spectrum corresponding to a diode pumped QX/Yb laser operating in a free running mode.

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

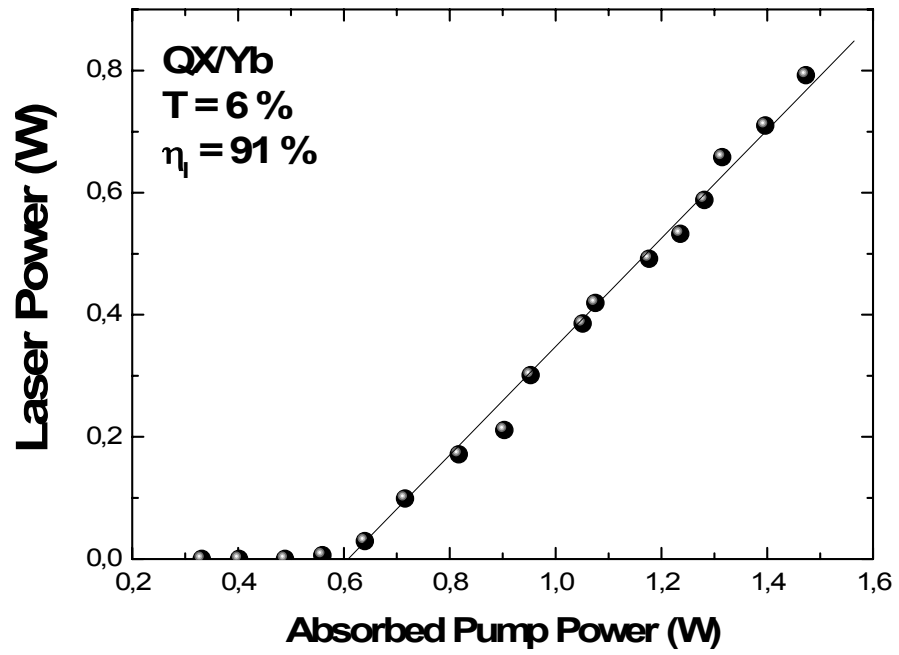
Figure 3.- Output laser power as a function of absorbed pump power. Output mirror transmittance was 6 %. Dots are experimental data and solid line is best fit to a linear relation.



D. Jaque et al. Figure 1.



D. Jaque et al. Figure 2.



D. Jaque et al. Figure 3.