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Efficient laser operation of an Yb:S-FAP crystal at 985 nm

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We have obtained three-level cw laser operation at 985 nm with a Yb-doped S-FAP bulk crystal pumped by a Ti:sapphire laser. An output power of 250 mW for an incident pump power of 1.45 W has been achieved, which is the highest cw output power ever obtained, to our knowledge, at this wavelength with a Yb-doped crystal. The experimental results are in good agreement with the numerical model that we have developed. © 2003 Optical Society of America

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1. Introduction

As the number of optical channels in the telecommunications area increases, there is a strong need for the development of new laser sources that emit an output power of a few watts around 985 nm with a good beam quality for the pumping of erbium-doped fiber amplifiers. Several ways have already been successfully studied, such as the development of novel semiconductor-based laser devices (for example, the extended-cavity surface-emitting laser,[1] the α-distributed-feedback laser,[2] or the optically pumped semiconductor[3]) or semiconductor laser diodes in external cavities.[4] Another solution to get a compact laser source emitting around 985 nm is to use ytterbium-doped (Yb-doped) materials. Depending on the host material, the Yb-doping ion can present a relatively large absorption band around 900 nm useful for diode pumping and a laser transition around 980 nm.[5] However, this is a true three-level laser transition, which implies a high pump power density to invert half of the total population density and to overcome the absorption at the laser wavelength. Moreover, a well-known laser oscillation around 1010–1050 nm is more favorable than the transition around 980 nm and is to be suppressed. Efficient operation of a Yb-doped silica-fiber laser around 980 nm has been obtained,[6] thanks to the possibility of achieving both extremely high pump intensities with a small core fiber and a good overlapping between the pump and the laser beams. In contrast, laser operation of a three-level Yb-doped bulk crystal around 980 nm is much more challenging because the pump-intensity requirements are so high that the oscillation threshold cannot generally be reached with pump sources of a few watts. The only Yb-doped crystal lasers at 985 nm reported in the literature are a long-pulse-pumping quasi-cw Yb:S-FAP laser[7] and a Ti:Sapphire-pumped cw Yb:C_4SFAP with a low slope efficiency (5%) and a high laser threshold (516 mW).[8] The aim of the present paper is to report efficient cw three-level laser operation at 985 nm with an Yb-doped bulk crystal. We introduce a selection criterion for the host material. Then we describe the experimental setup and expose the results obtained with the crystal selected as well as comparisons with our numerical model.

2. Choice of the Crystal

Many crystals have been reported in the literature to serve as host materials for Yb. As the laser threshold is difficult to achieve in three-level lasers, we have chosen the pump intensity I_p necessary to reach transparency as a selection criterion for the host material.I_p is the pump intensity (in kilowatts per square centimeter) above which the gain coefficient $g = \sigma_{el}N_2 - \sigma_{al}N_1$ is positive, with N_2 and N_1 as the population densities of the upper and lower manifolds, respectively, σ_{al} as the effective absorption cross section at the laser wavelength, and σ_{el} as the

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Table 1. Estimation of the Transparency Pump Intensity I_p for Different Yb-Doped Materials[a]

Host Material	λ_p (nm)	λ_l (nm)	σ_{al} (10^{-20} cm^2)	σ_{ap} (10^{-20} cm^2)	σ_{el} (10^{-20} cm^2)	τ (ms)	I_p (kW/cm^2)
GdCOB[9]	900	976	1.2	0.5	0.5	2.74	38
$LiYO_2$[5]	908	972	0.8	1.2	0.5	1.13	26
YAG[10]	941	968	0.75	0.77	1	0.95	22
Tungstate (KGW)[11]	935 ($E\|\|a$)	981 ($E\|\|a$)	12	2.5	16	0.6	10
Apatite (S-FAP)[12,13]	900 ($E\|\|c$)	985 ($E\perp c$)	10	9	10	1.14	**2**

[a] σ_{ep} is negligible for these materials. λ_l is the laser wavelength.

effective emission cross section at the laser wavelength. When there is no laser intensity in the cavity, the gain coefficient g can also be written as[9]

$$g = N\frac{(\sigma_{el}\sigma_{ap} - \sigma_{al}\sigma_{ep})\dfrac{\lambda_p}{hc}I_p - \dfrac{\sigma_{al}}{\tau},}{(\sigma_{ap} + \sigma_{ep})\dfrac{\lambda_p}{hc}I_p + \dfrac{1}{\tau}}, \qquad (1)$$

with σ_{ep} as the effective emission cross section at the pump wavelength, σ_{ap} as the effective absorption cross section at the pump wavelength, τ as the fluorescence lifetime, and λ_p as the pump wavelength.

So I_p is given by

$$I_p = \frac{hc\sigma_{al}}{(\sigma_{el}\sigma_{ap} - \sigma_{al}\sigma_{ep})\,\tau\lambda_p}. \qquad (2)$$

On Table 1 we have reported I_p for several host materials. Note that the intrinsic lifetime, i.e., the fluorescence lifetime without the effect of radiation trapping, is reported for only a few Yb-doped crystals (Yb:YAG,[10] Yb:S-FAP,[11] and Yb:KYW[14]). Moreover, a complete set of spectroscopic parameters (comprising intrinsic lifetime and cross sections at the pump wavelength around 900 nm and at the laser wavelength around 980 nm) was reported only for Yb:YAG[10] and Yb:S-FAP.[12,13] For the other crystals mentioned in Table 1, we used the fluorescence lifetimes given in the literature, which may be overestimated with respect to the intrinsic lifetimes.[10] Nevertheless, the order of magnitude of I_p should not be affected.

As evidenced by Table 1, the apatite structure appears to be the most favorable crystal host, owing to its high cross sections. In the apatite family the laser and spectroscopic properties of Yb-doped $Sr_5(PO_4)_3F$ or S-FAP are among the most studied in the literature.[7,8,12,13] Moreover, Yb:S-FAP has already been shown to be an ideal laser material in diode-pumped solid-state laser oscillator systems.[15,16] So we have chosen to use Yb:S-FAP to demonstrate efficient cw three-level laser operation at 985 nm.

3. Experimental Setup

Figure 1 shows the experimental setup. The laser rod is a 4-mm-long cube. The crystal is antireflection coated at 900 and 985 nm on both faces. The Yb concentration is 1.9×10^{19} ions/cm^3. The crystal is end pumped along the $E\|\|c$ axis, and lasing at 985 nm will be preferentially along the $E\perp c$ axis. We have used a Ti:Sapphire laser emitting a maximum output power of 1.45 W at 900 nm in a nearly TEM$_{00}$ beam to demonstrate the possibility of achieving cw operation at 985 nm with an Yb:S-FAP crystal. The pump beam is focused inside the laser rod by a 100-mm focal-length lens, and the pump-beam-waist size radius in the crystal is measured to be approximately 80 μm. We have used a nearly concentric cavity with mirrors having a curvature radius of 100 mm. This provides a laser-mode waist size in the crystal of approximately 40 μm. The three-level nature of the transition requires the laser mode in the gain medium to be highly overlapped by the pump beam. The input mirror (Laseroptik GmbH) is highly transmissive at 900 nm and highly reflective at 985 nm. The output mirror (VLOC) is highly reflective at 900 nm in order to recycle the pump laser beam. Moreover, both input and output mirrors are highly transmissive around 1047 nm to suppress laser oscillation on this transition. The transmission of the output coupler is 7% at 985 nm.

4. Laser Operation

Lasing action is easily obtained at 985 nm with no parasitical laser oscillation at 1047 nm. We have obtained an output power of 250 mW at 985 nm in a TEM$_{00}$ laser beam for an incident pump power of 1.45 W. Laser threshold is reached for an incident pump power of 200 mW. The slope efficiency with respect to the incident pump power is 20%. We have reported the output power at 985 nm versus the incident pump power on Fig. 2 as well as a picture of the spatial profile of the laser beam to illustrate its good quality. We have also plotted the theoretical output power versus the incident pump power predicted by our numerical model. This model is inspired from the one described in Ref. 9. To take into account the

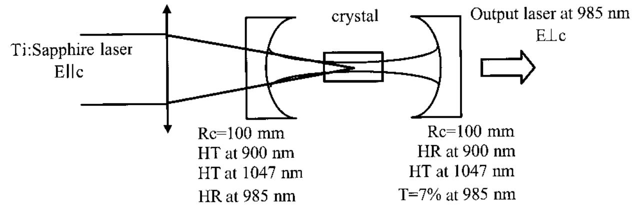

Fig. 1. Experimental setup. Rc, curvature radius; HT, highly transmissive, HR, highly reflective.

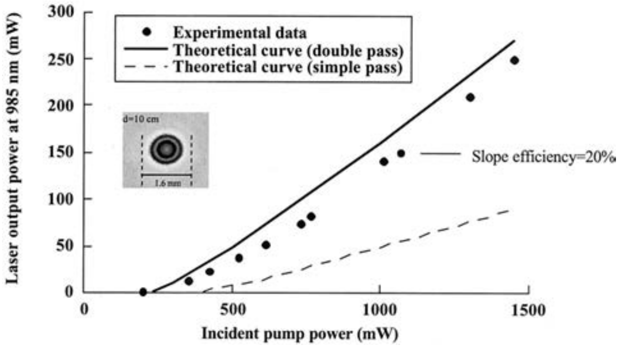

Fig. 2. Experimental (circles) and theoretical output power at 985 nm with (solid curve) and without (dashed curve) recycling of the pump versus incident pump power at 900 nm for an output coupler of 7%. Picture of the spatial profile of the laser beam at a distance $d = 10$ cm from the crystal. The size of the beam diameter at $1/e^2$ is 1.6 mm in both horizontal and vertical directions.

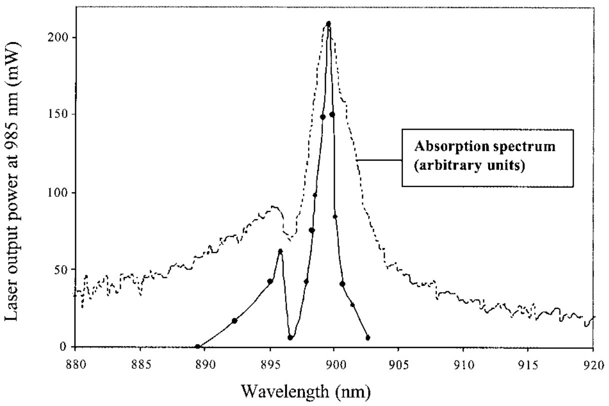

Fig. 4. Output power at 985 nm versus the wavelength of the pump Ti:Sapphire laser for anincident pump power of 1.45 W (bold curve). Comparison with the absorption spectrum of the Yb:S-FAP in arbitrary units (dashed curve).

true three-level nature of the laser, our model calculates the small-signal gain per double pass integrated over the whole crystal without neglecting the saturation of absorption. Moreover, we have added the recycling of the pump in the expression of the small-signal gain. The adjustable parameter is the double-pass passive losses, which were estimated to be approximately 5%. Figure 2 shows that our experimental data are in good agreement with this numerical model. On Fig. 2 we have also plotted the theoretical output power versus the incident pump power without the recycling of the pump. This shows that the recycling of the pump increased the slope efficiency by a factor of 2.8.

5. Small-Signal Gain Measurements

We also measured the small-signal gain as it is an important parameter for a laser medium. These small-signal gain measurements were carried out by varying the losses in the cavity with the use of different output couplers or the insertion of glass plates or both. On Fig. 3 we have plotted the theoretical small-signal gain with and without the recycling of the pump as well as the experimental small-signal gain versus the pump power. As evidenced by Fig. 3, the recycling of the pump permitted a decrease in the laser threshold pump power by a factor of 1.8 (the intersection between the gain curves and the loss curve gives the incident pump power at threshold). Actually, the saturated absorption of the pump on one pass was quite low (approximately 20%), and the double pass of the pump provided a more efficient population inversion along the whole crystal. In this configuration the theoretical small-signal gain is as high as 2.8 for maximum available pump power. Experimentally, we have reached laser threshold with an equivalent output coupler of 61%, corresponding to a small-signal gain of 2.62. This is a relatively high small-signal gain for a solid-state laser, allowing the introduction of quite important losses in the cavity. Moreover, such a crystal could be also useful for amplification. Figure 3 shows that the experimental results are in good agreement with the predictions of our model.

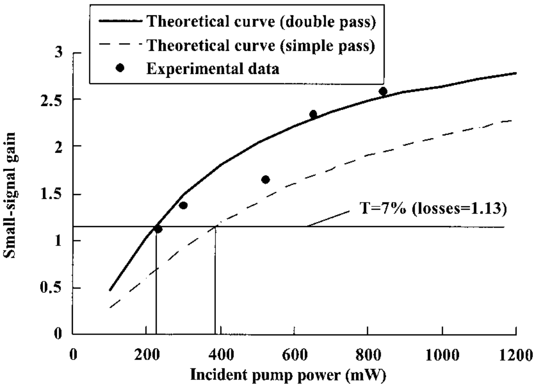

Fig. 3. Experimental (circles) and theoretical small-signal gain with (solid curve) and without (dashed curve) recycling of the pump versus incident pump power.

6. Discussion on Diode Pumping

As the ultimate aim of this laser is to be diode pumped, it is interesting to evaluate the pump spectral bandwidth that can lead to laser oscillation at 985 nm. On Fig. 4 we have plotted the output power at 985 nm versus the wavelength of the Ti:Sapphire pump laser λ_p for an incident pump power of 1.45 W. Laser oscillation occurs from $\lambda_p = 889.5$ nm to $\lambda_p = 902.7$ nm, and the full width at half-maximum of the main peak is approximately 1.8 nm, in the same range as the spectrum of laser diodes emitting an output power of 2 W with an emitting surface area of 1×100 μm. Moreover, we have adapted our numerical model to diode pumping by taking into account the higher size of the pump beam at the focused point and the degradation of the diode pump beam in the slow axis direction with a beam-propagation factor M^2 of 15. This has shown that laser operation could also be achievable with the kind of diode mentioned above. As shown on Fig. 5, our model predicted that the slope efficiency would be reduced by a

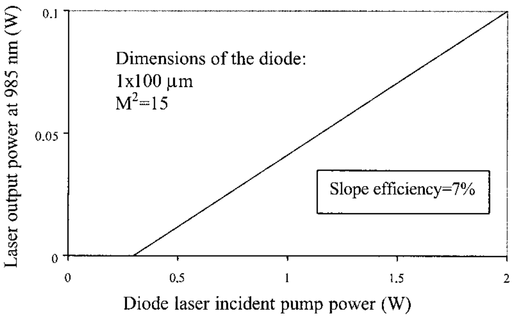

Fig. 5. Predictions of the output power versus incident pump power from our numerical model adapted to the diode pumping.

factor of 3 and the laser threshold would be raised to 300 mW of incident pump power. An output power of 100 mW at 985 nm would be obtained at the maximum pump power of 2 W. These preliminary results are promising for the diode pumping of Yb: S-FAP crystals at 900 nm.

7. Conclusion

In conclusion, the evaluation of the pump intensity at threshold for different crystals has led us to use an Yb:S-FAP crystal to achieve efficient cw three-level laser operation at 985 nm. An output power of 250 mW has been obtained for an incident pump power of 1.45 W, and laser threshold has been reached for an incident pump power of 200 mW, leading to a slope efficiency with respect to the incident pump power of 20%. This is, to our best knowledge, the highest cw output power ever obtained with an Yb-doped crystal at this wavelength. This demonstration with a Ti: Sapphire laser is the first step to the diode pumping of an Yb:S-FAP crystal at 900 nm for cw laser emission at 985 nm.

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