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DIODE-PUMPED Yb:S-FAP THIN-DISK LASER OPERATING AT 985 nm AND THE SECOND-HARMONIC GENERATION AT 492.5 nm

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Abstract

We report a diode-pumped continuous-wave (CW) thin-disk Yb^{3+}-doped $Sr_5(PO_4)_3F$ (Yb:S-FAP) laser operating at 985 nm. We achieve a power of 4.34 W at 980 nm in the CW operation regime with a fiber-coupled laser diode emitting 17.2 W at 914 nm. Furthermore, we demonstrate intracavity second-harmonic generation in the continuous-wave mode with a power of 893 mW at 492.5 nm using a BiB_3O_6 (BiBO) nonlinear crystal. The fluctuation of the blue output power was better than 3.57%. The M_2 factors are about 1.15 and 1.18 in the X and Y directions, respectively.

Keywords: diode-pumped thin-disk laser, Yb:S-FAP crystal.

1. Introduction

Since Fan and Byer have introduced the first diode-laser-pumped 946 nm Nd:YAG laser operating at room temperature in 1987 [1], lasers operating in the range around 0.9 μm attracted much attention in the past few years. This is due to their unique application such as water vapor lidars and differential absorption lidars for ozone measurements; also they can be used as the pump sources for the Yb-doped crystals and Yb-doped optical fibers. The quasi-three-level 0.9 μm CW laser emission was widely investigated using Nd-doped crystals [2–10], and the lasers operating in the range around 980 nm have been studied for many applications. For example, to pump erbium-doped fiber amplifiers, one needs laser sources emitting at least a few watts at this wavelength with good spatial beam quality. Moreover, using nonlinear crystals, the blue range around 0.49 μm is achievable. This is close to the argon laser line at 488 nm, which is still used in fluorescence spectroscopy and biological applications.

The main problems relative to argon lasers are their size and very restrictive maintenance. Solid-state lasers are a good alternative due to their compactness and efficiency. For diode-pumped solid-state lasers,

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there are two ways to reach a blue range around 490 nm. One way is to design lasers using crystals doped with ions directly emitting in the blue such as Dy^{3+} [11]. The other way is to develop lasers emitting at the lowest wavelength possible in the near infrared [12] and to perform nonlinear conversion [13–25]. An Yb-doped apatite has spectroscopic and laser properties that make them useful to be employed as laser materials. In particular, recent experimental work with Yb:S-FAP has shown that this material is a promising candidate for high-energy laser systems due to its long storage lifetimes.

From the spectroscopy of the Yb:S-FAP [26], we can see that the emission cross section of 985 nm is 10^{-19} cm^2, and the emission cross section of 1,047 nm is only $\sim 10^{-19}$ cm^2, so the emission of 985 nm is strong enough, and the 1,047 nm emission can be suppressed completely [27,28]. Furthermore, the strong pump and emission lines at 0.9 μm make this material highly appropriate for diode pumping thereby increasing the overall efficiency of the system.

Recently, a new way to reach a range around 0.49 μm is to use the Yb:S-FAP laser emitting at 985 nm and being intracavity pumped at 914 nm by the Nd:YVO_4 laser. This original pumping scheme allows one to provide an efficient laser action on a three-level transition at 985 nm with an 1.4 W output power. Furthermore, intracavity second-harmonic generation has also been demonstrated with a power of 120 mW at 492.5 nm using a LBO nonlinear crystal [29]. Because of the weakness of the absorption at 0.91 μm in the Yb:S-FAP, this solution is still limited.

In this paper, we report on a laser-diode-pumped CW Yb:S-FAP thin-disk laser operating at 985 nm; up to our knowledge, for the first time. The use of a pump module with 16 passes through the crystal allows one to realize a Yb:S-FAP thin-disk laser with 4.34 W of CW output power. The overall absorption within the 16 passes is equal only about 3% of the pump power, which can be neglected. The slope efficiency is up to 32.9%, and the fluctuation of the output power is better than 3.5%. Furthermore, we demonstrate a CW 492.5 nm laser based on intracavity frequency-doubling Yb:S-FAP-BiBO.

2. Experimental Setup

In Fig. 1 a, we show the experimental setup of the fundamental 1,034 nm laser used. The optical pumping at 914 nm was realized by a fiber-coupled diode laser of LIMO Co., Germany. The maximum CW output power delivered by this prototype diode was 20 W and the width of the emission spectrum was $\sim$2.5 nm. The pump diode is coupled into a 400 μm core-diameter fiber demonstrating a 0.22 NA. The laser crystals used in the experiments were 1.5 at% Yb:S-FAPs. The crystal thickness was 0.3 mm. The thin-disk crystal was antireflection (AR) coated at the front side and high-reflection (HR) coated at the rear side for the pump and laser wavelengths. The rear side was soldered onto a water-cooled heat sink with a coolant temperature maintained at 15°C. The parabolic mirror (32 mm focal length) and the folding prisms lead to a 16-pass pump scheme. The radii of curvature of the first mirror M1 was 50 mm. The first mirror M1 of the cavity is highly reflective at 985 nm. The second mirror M2 is a 97% transmission output coupler at the lasing wavelength. As the best performance was obtained at 985 nm, we tried to reach the second-harmonic generation at this wavelength. We modified the cavity to reduce the cavity losses and add a second waist. All the elements were the same as the corresponding ones in the setup of the fundamental 985 nm laser mentioned above. A concave mirror M3 was coated with HR at 985 nm and AR at 492.5 nm. A concave mirror M4 was coated with HR at 985 and 492.5 nm.

In Fig. 1 b, we show the experimental setup of the intracavity frequency-doubled 492.5 nm laser. The BiBO crystal cut for Type-I critical phase matching in the principal plane XY ($\theta = 133.3°$ and $\phi = 90°$, with $d_{\text{eff}} = 2.38$ pm/V) was chosen as the nonlinear crystal. The size of the BiBO crystal is 2×2×10 mm, and both end facets were presented by the BiBO crystal. The BiBO is mounted in a copper block, which is also fixed on a thermoelectric controller for active temperature control.

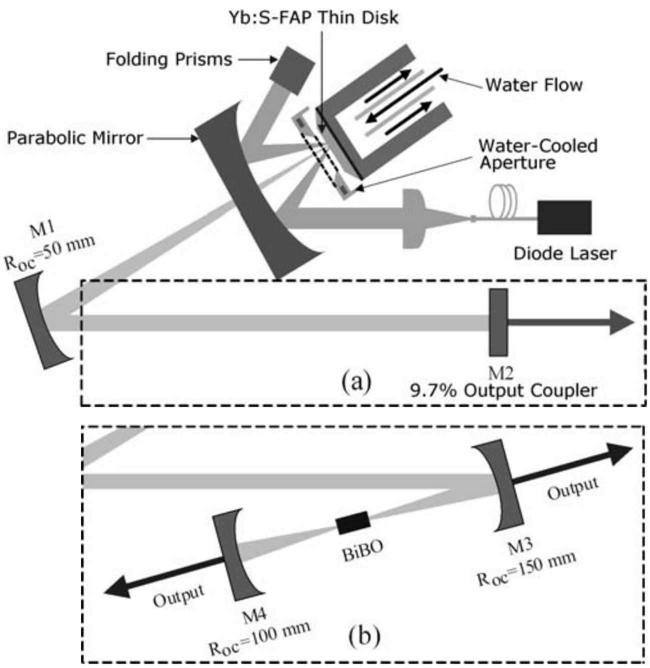

Fig. 1. Schematic diagrams of the experimental setup for the fundamental 985 nm laser (a) and for the frequency-doubled 492.5 nm laser (b).

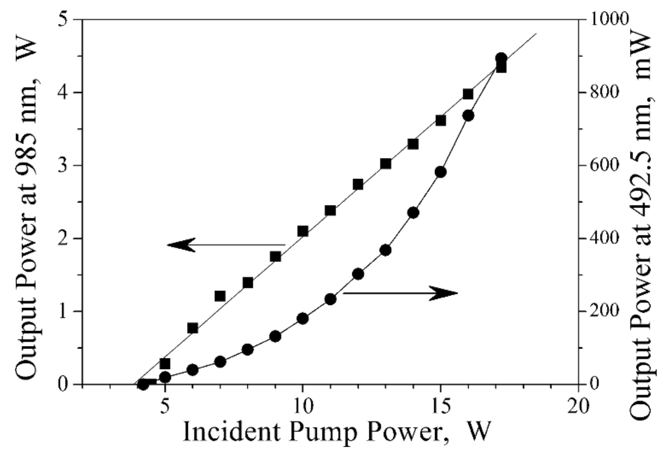

Fig. 2. Output power at 985 nm (■) and at 492 nm (●) versus the incident pump power at 914 nm; the slope efficiency is equal to 32.9%.

3. Results and Discussion

In Fig, 2, we show the output power at 985 nm versus the incident pump power at 914 nm. The output power is linearly increasing with respect to the incident pump power, demonstrating a measured pump threshold of 4.5 W and a slope of 32.9%. The highest output power of 4.34 W was achieved for an incident pump power of 17.2 W and an optical conversion efficiency of 25.1%. We used the algorithms of the knife-edge technique [30] to determine the beam width for various positions of the laser beam along the optical axis in the focused beam-waist region and in the far field, respectively. The values of the M^2 factor were determined via a hyperbolic fit to the experimental data. The M^2 factors are about 1.13 and 1.15 in the X and Y directions, respectively.

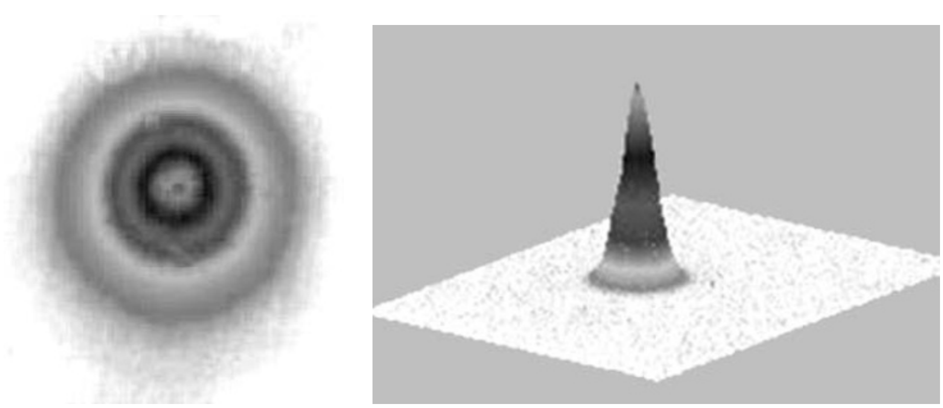

Fig. 3. The beam profile distribution of the 985 nm laser.

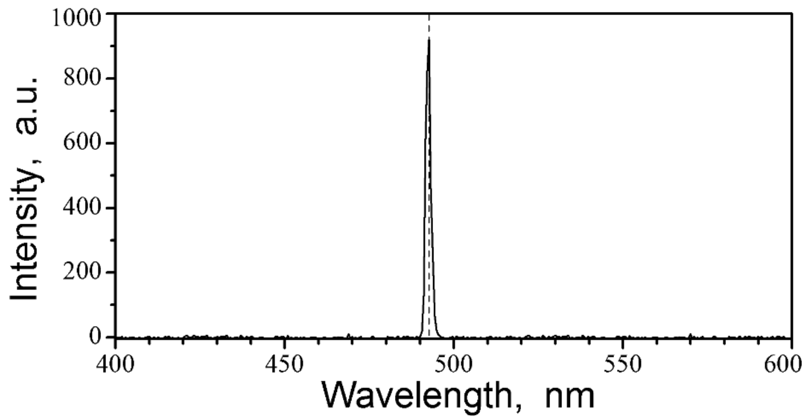

Fig. 4. The spectrum of the 492.5 nm blue laser.

The laser beam profile in Fig. 3 was measured at a pump power of 17.2 W using the beam profiler made by Photon Inc. The measured beam profile was TEM_{00} and the ellipticity of spot was 0.987. In Fig, 3, the blue laser performance is also presented. The threshold of the 492.5 nm laser was about 4.2 W. With an incident pump power of 17.2 W, a CW second-harmonic-generation output power of 893 mW at 492.5 nm emission was obtained. The M^2 factors are about 1.15 and 1.23 in the X and Y directions, respectively. The asymmetry of the M^2 factor in the two directions is a result of the walk-off between the fundamental wave and the second harmonic in the direction of the BiBO.

The stability testing was carried out by monitoring the blue-green laser with a Field-Master-GS powermeter at 10 Hz. The fluctuation of the output power was about 3.57% during 4 hours. The spectra were measured with a Spectrapro-500i spectrometer; see Fig. 4. The spectral line width (FWHM definition) is about 0.75 nm with the central wavelength at 492.5 nm.

4. Conclusions

In summary, we demonstrated, to the best of our knowledge, for the first time, the laser emission at 985 nm in Yb:S-FAP crystals in thin-disk configuration. For the 985 nm emission, with a 0.3 mm long, 1.5 at.% doped crystal, a CW output power of 4.34 W was achieved for an incident pump power of 17.2 W. Our results show that the Yb:S-FAP Yb:S-FAP is a potential 985 nm laser crystal for high-power systems. After the second-harmonic generation, we obtained a blue–green power of 893 mW at 492.5 nm. The use of more efficient nonlinear crystals, such as PPKTP or $KNbO_3$, should increase the second=harmonic radiation power.

Acknowledgments

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