Yb:S-FAP Multipass Side-Pumped Amplifier

Bhabana Pati, Yelena Isyanova, Kevin F. Wall, and Peter F. Moulton

Q-Peak, Inc., 135 South Road, Bedford, MA 01730
pati@qpeak.com

Abstract: We report a diode side-pumped, single-stage, multi-pass Yb:S-FAP amplifier designed to achieve high pump brightness, uniform absorption, and high amplification. We demonstrate highly efficient operation of the amplifier with an input signal from a Nd:YLF oscillator.

OCIS Codes: (140.3580) Lasers, solid-state (140.3480) Lasers, diode-pumped

1. Introduction

Highly efficient, multi-pass-slab (MPS), side-pumped configurations have been successfully demonstrated for Nd:YLF [1], Nd:YVO_4 [2], and Er:YLF [3] four-level lasers. Side pumping eliminates the connection between the absorption and gain length of the laser material, thus providing a means to scale the output power. However, compared to four-level materials, limitations on MPS designs are more an issue for quasi-three level materials because of the high pump brightness required to overcome the thermal population of the lower laser level. Nonetheless, side pumping of quasi-three-level laser materials has been recently shown to be a promising technique for Yb:YAG [4] and Yb:S-FAP [5] diode-pumped lasers. In this paper, we present a side pumped, single-stage, multi-pass Yb:S-FAP amplifier designed to achieve high pump brightness, uniform absorption, and high amplification.

2. Experiment and results

The multi-pass, side-pumped design of the Yb:S-FAP amplifier is shown in Fig. 1. Two diode lasers are used in an offset configuration to pump a 2 x 8 x 22 mm, 1-%-doped, Yb:S-FAP laser slab. The c axis of the slab is perpendicular to the largest faces (8 x 22 mm) of the slab. The pump faces of the slab have segmented dielectric coatings (AR/HR) to double-pass the pump light through the slab. The heat from the slab is extracted by contacting the top and bottom of the slab to the copper heat sink, thus separating the pumping and cooling faces. This method of heat deposition and removal is particularly attractive for low-thermal-conductivity material such as Yb:S-FAP.

The diode-laser wavelength and its spectral width, 900 nm and 3 nm, respectively, were chosen to correspond to those of the strong π-absorption line of Yb:S-FAP. The polarization of the pump beam, which is parallel to the diode junction, was adjusted using a half-wave plate to make it parallel to the c-axis, to utilize the π-absorption line. The diode lasers were water-cooled and temperature-controlled to reach the optimum pump wavelength. For the diodes we had available, at the same temperature there was a 2-nm difference in peak emission, leading to lower absorption efficiency. The pump light was collimated in the fast axis to obtain a beam height of 300 μm. Total maximum peak pump power and power intensity achieved were 160 W and 2.4 kW/cm^2, respectively. The maximum pump intensity was higher than the Yb:S-FAP saturation intensity, which is equal 2.0 kW/cm^2 [6].

Prior to our experimental effort, we calculated the gain for a 1% Yb:S-FAP crystal when pumped by the diode lasers run quasi-cw at 90 W peak power, 1.2 msec duration in a double-pass pump configuration. The pump beam was approximated by a flat-top beam (1 cm x 0.03 cm) in both axes with no divergence. We assumed that the crystal temperature was a uniform 50˚C and calculated the Boltzmann factors for the various levels accordingly. Other parameters that were input to the model are listed in Table 1.

The steady-state rate equations describing the absorption of the pump light in a quasi-three-level system [7] were solved numerically to first find the pump intensity as a function of distance in the Yb:S-FAP crystal. From the intensity distribution we next calculated the population in the ground state manifold and upper manifold. Using the Boltzmann factors, we then calculated the gain as a function of distance. The results of these calculations are shown in Fig. 2, where the square data points are the calculated intensity normalized to the saturation fluence and the diamond data points are the calculated gain. The figure shows the result for double-pass pumping with one pump-diode laser only.

Table 1. Model parameters

Parameter	Value
Temperature of gain region	50 ˚C
Absorption cross-section (π polarization)	8.39 x 10^{-20} cm^2
Pump wavelength	900 nm
Upper laser level lifetime	1.23 ms
Boltzmann factor for ground state	0.789
Boltzmann factor for pump level	0.008
Boltzmann factor for upper laser level	0.588
Boltzmann factor for lower laser level	0.05
Total number of Yb ions	1.1 x 10^{19}
Stimulated emission cross section	7.3 x 10^{-20} cm^2

An input signal to the Yb:S-FAP amplifier was provided from a fiber-coupled-diode, end-pumped, passively Q-switched, 1047-nm Nd:YLF oscillator followed by a Nd:YLF pre-amplifier. The oscillator had a semi-concentric cavity and produced a single-frequency, TEM_{00}-mode beam with a pulse energy of 1 mJ and pulse width of 20 nsec. The output pulses were amplified to ~ 4 mJ energy per pulse by the Nd:YLF amplifier. The layout of the whole system is shown in Figure 3. The configuration of the Nd:YLF gain module [1] was in general similar to that of the Yb:S-FAP amplifier. The output beam from the Nd:YLF amplifier was collimated and shaped to an elliptical beam of ~ 1.2 mm x 0.3 mm to match the cross-sectional size of the gain sheet in the Yb:S-FAP slab. In order to provide five or seven passes, we used high-reflectivity mirrors as shown in Fig. 1. The mirrors were cylindrical, with cylindrical surfaces aligned in the vertical plane, allowing us to maintain a 300-μm beam height through the Yb:S-FAP slab.

The oscillator, the Nd:YLF pre-amplifier, and the Yb:S-FAP amplifier were operated in quasi-cw mode at a 50 Hz repetition rate, with pump-pulse durations of 0.5 msec, 0.5 msec and 1.2 msec, respectively. The Q-switched laser pulses were synchronized to arrive at the end of the 1.2-msec, Yb:S-FAP pump pulse. We first measured a single-pass gain of the Yb:S-FAP amplifier without external HR mirrors. The dual goal for these measurements was to verify our gain modeling and determine the uniformity of the gain distribution. Using a 0.8-mJ oscillator beam we probed the single-pass gain at 80-W of peak power per diode. The gain was found uniform throughout the entire cross section of the Yb:S-FAP slab and equal 1.5, in good agreement with the data presented in Fig. 2.

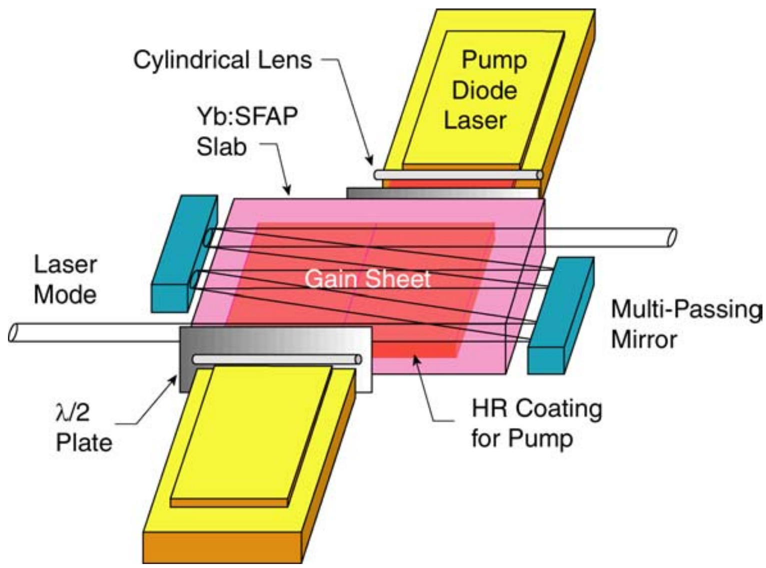

Fig. 1. Schematic of the Yb:S-FAP amplifier.

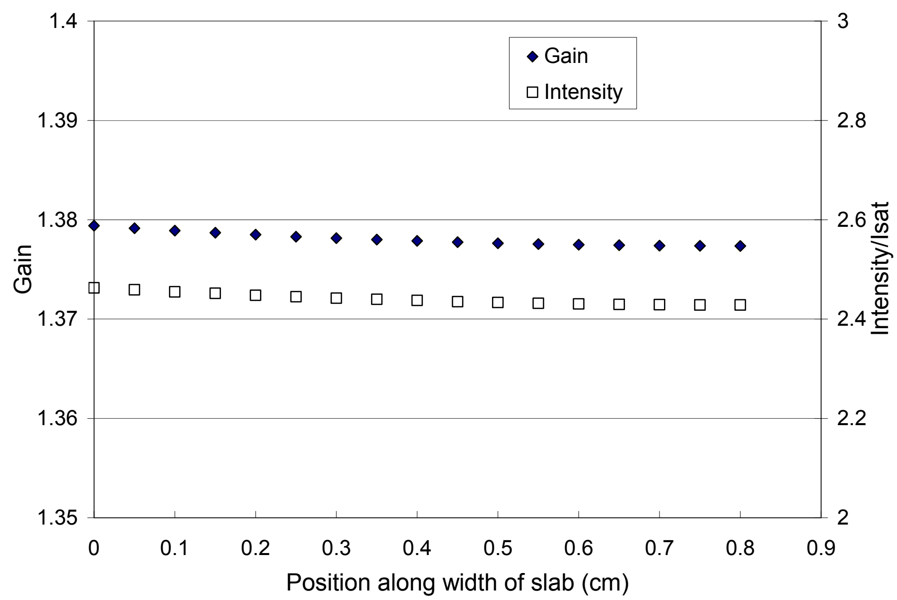

Fig. 2. The calculated normalized pump intensity (square) and gain (diamond) as a function of position along the 8-mm face of the Yb:S-FAP slab.

We then measured the output energies from the Yb:S-FAP amplifier with HR multi-passing mirrors as a function of the pump power at different input energies and number of passes. It can be seen from the data plotted in Fig. 4 that, using the five-pass configuration and a 4-mJ input beam, we achieved a maximum output energy of 16 mJ. With the seven-pass configuration, the maximum output energy, ~18 mJ, was not substantially higher than that of the five-pass configuration. This is indicative of gain saturation. The output beam profile was nearly Gaussian in both horizontal and vertical planes for all of the tested configurations.

Using the results of the gain modeling, we conducted calculations on Yb:S-FAP amplification based on the Frantz-Nodvick analysis [8]. The results of calculations of the Yb:S-FAP output energies as a function of input energies are plotted in Fig. 4. Also plotted are some corresponding experimental data from Fig. 3 that are in good agreement with predicted values. In particular, the maximum energy obtained was 16 mJ, only 2 mJ less than the value predicted.

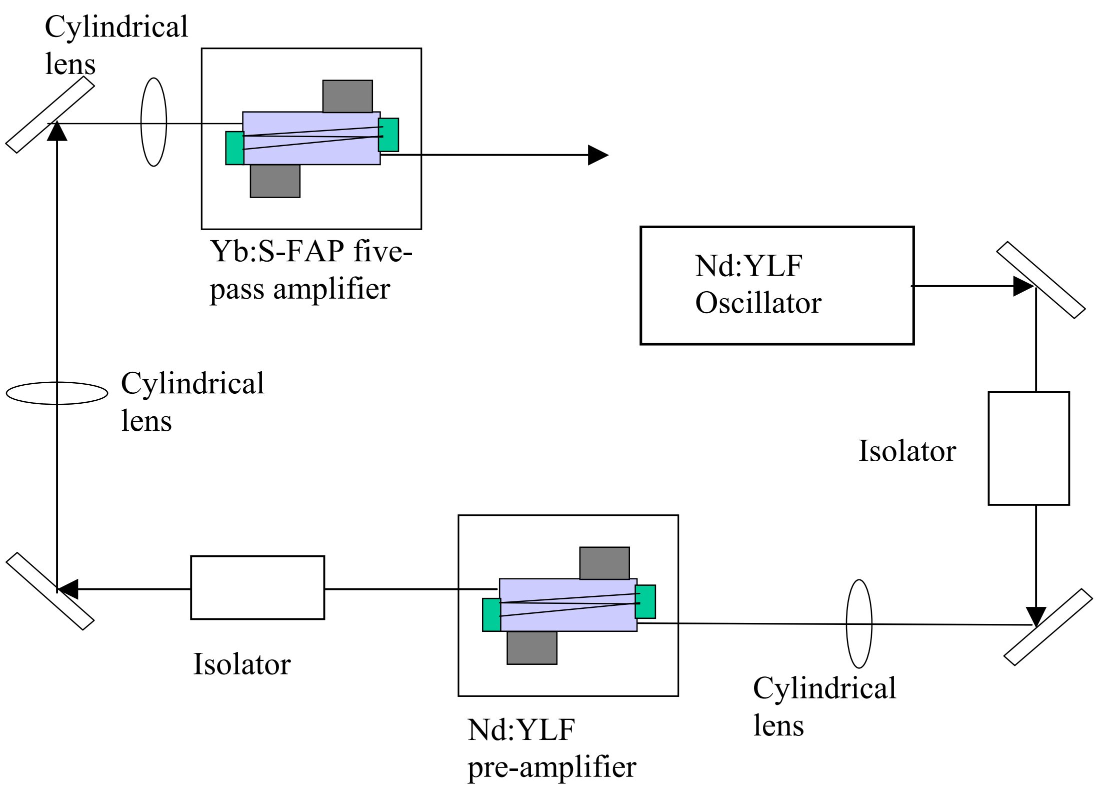

Fig. 3. Experimental layout.

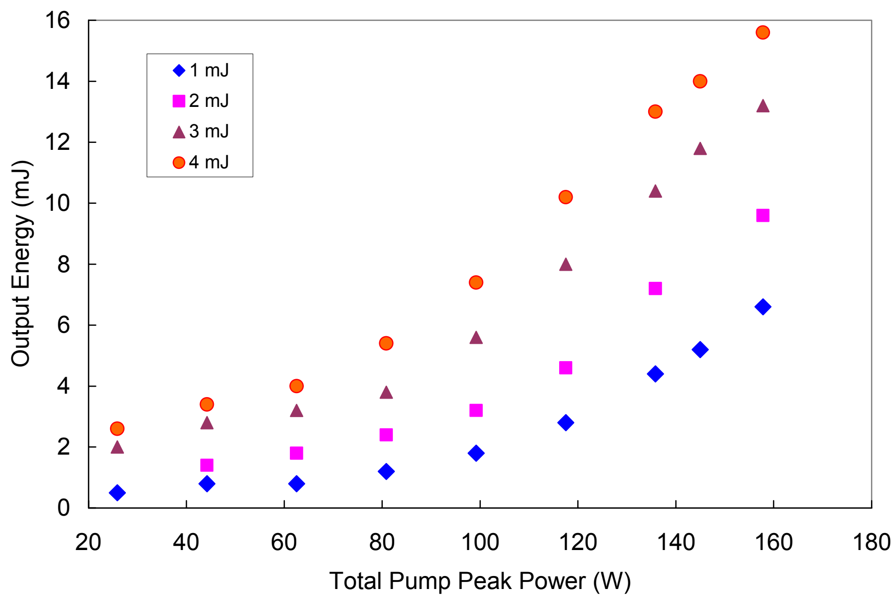

Fig. 4. Output pulse energy as a function of pump power at different input pulse energies for five-pass amplification.

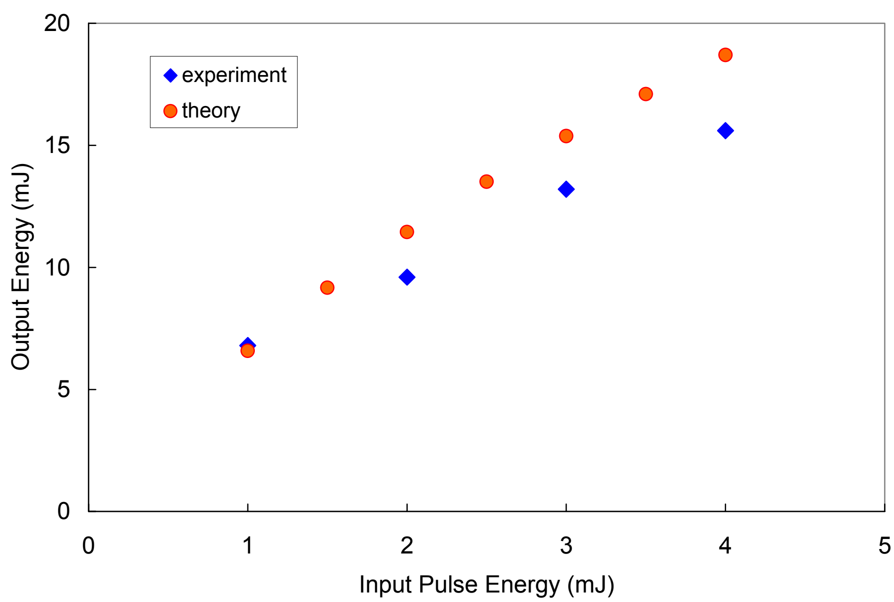

Fig. 5. Yb:S-FAP five-pass amplification for different input pulse energies at total pump power of 160 W.

3. Conclusion

We have demonstrated the first, to our knowledge, diode side-pumped, multi-pass Yb:S-FAP amplifier. Using quasi-CW diode lasers with peak powers of 80 W and pulse widths of 1.2 ms, we obtained a maximum slope efficiency of 14% with 16 mJ of energy per output pulse. An excellent agreement with theoretical calculations allowed us to verify that our approach to designing a side-pumped amplifier based on three-level laser material is viable. Higher efficiencies are possible with a higher-doped Yb:S-FAP and better matching of the diode laser wavelength as well as spectral linewidth to those of Yb:S-FAP.

4. Acknowledgement

We wish to thank K. I. Schaffers and A. J. Bayramian at Lawrence Livermore National Laboratory for supplying Yb:S-FAP material and for insightful discussions on its properties. This work was supported by the US Air Force, Contract # F29601-02-C-0011.

5. References

1. K. J. Snell, D. Lee, K. F. Wall, and P. F. Moulton, "Diode-pumped, high-power CW and modelocked Nd:YLF lasers," *OSA Trends in Optics and Photonics Vol 34, Advanced Solid-State Lasers*, Hagop Injeyan, Ursula Kelloer, and Christopher Marshall, eds., (Optical Society of America, Washington, DC 2000) pp. 55-59.
2. K. J. Snell, D. Lee, "High average power, high repetition rate side-pumped Nd:YVO_4 slab laser," *OSA Trends in Optics and Photonics Vol 26, Advanced Solid-State Lasers*, M. M. Fejer, H. Injeyan, and U. Kelloer (eds), (Optical Society of America, Washington, DC 1999) pp. 295-297.
3. A. Yu. Dergachev, J. H. Flint, and P. F. Moulton, "1.8-W CW Er:YLF diode-pumped laser," in Conference on Laser and Electro-optics, on OSA Technical Digest (Optical Society of America, Washington, DC 2000) pp. 564-565.
4. T.S. Rutherford, W. M. Tulloch, E. K. Gustafson, and R. L. Byer, "Edge-pumped quasi-three-level slab lasers: Design and power scaling," IEEE. J. Quantum Electron., **36,** 205 (2000).
5. A. Dergachev, Y. Isyanova, P. F. Moulton, and K. I. Schaffers, "A CW side-pumped Yb:S-FAP laser," OSA *Trends in Optics and Photonics Vol. 68, Advanced Solid-State Lasers, Martin E. Fermann and Larry R. Marshall, eds.*(Optical Society of America, Washington, DC 2002), pp. 563-565.
6. S. A. Payne, L. D. DeLoach, L. K. Smith, W. L. Kway, J. B. Tassano, B. H. T. Chai, and G. Loutts, "Ytterbium-doped apatite-structure crystals: A new class of materials," J. Appl. Phys. **76** (1), 497, (1994).
7. T. Y. Fan, "Optimizing the efficiency and stored energy in quasi-three-level lasers," IEEE J. Quantum Electronics, **28**, 2692 (1992).
8. M. Frantz and J.S. Nodvick, "Theory of pulse propagation in a laser amplifier," J. Appl. Phys., **34**, 2346 (1963).