High gain (43 dB), high power (40 W), highly efficient multipass amplifier at 995 nm in Yb:LiYF₄*

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Abstract—A simple implementation of a multipass amplifier along with the use of a cryogenic Yb:LiYF₄ (YLF) gain medium has enabled the demonstration of a bulk amplifier with an unprecedented combination of large-signal gain (43 dB), efficiency (>50% optical), average output power (40 W) and a near-diffraction-limited output beam.

Index Terms—Laser amplifiers, Ytterbium lasers

I. INTRODUCTION

HIGH-gain flexible-waveform optical amplifiers are needed in applications such as communications and lidar, and high efficiency for such amplifiers is desired as well, particularly in high average power laser systems. Optical fiber amplifiers work well for cw or high-duty cycle waveforms, but can be problematic as the power (both peak and average) increases because of optical nonlinearities and damage. In bulk amplifiers, high gain has been demonstrated by multipassing the gain medium. For short pulses, regenerative amplifiers are often used; however, they are limited to waveforms with short pulses and can have operational regimes of large pulse-to-pulse energy fluctuations. Also, they require high-speed electro-optic switching. Angular multi-passing [1–15] has been used less frequently; relative to a regenerative amplifier [16–18], it has the advantages of waveform flexibility and no electro-optic switch but the disadvantage that the number of passes is more limited.

Here a simple implementation of a multipass amplifier is demonstrated, and by using a cryogenically cooled gain element, excellent performance in terms of large-signal gain, average power, efficiency and beam quality has been attained. Cryogenic Yb gain elements enable high average power with minimal thermo-optic effects. Cryogenic Yb:YAG amplifiers [12,19–22] have previously been shown to operate nearly ideally at >100 W average power. Here, cryogenic Yb:YLF [23,24] is chosen as the gain medium because of the low thermal dissipation compared with Yb:YAG.

II. MULTIPASS AMPLIFIER IMPLEMENTATION

A schematic of the multipass amplifier is shown in Fig. 1. This implementation is based on other multipass amplifier implementations using 4f imaging [1–5,7-8] to bring the various passes to the gain element at different angles. This enables a large number of passes using relatively few optical elements and relatively simple alignment compared with implementing the multiple passes using a mirror array [9,11-13]. There are only three main components, the gain element, a lens, and a pair of mirrors oriented at 90 degrees with respect to each other. This mirror pair easily could be replaced by a right-angle prism with a flat polished onto the apex [4]. To reduce amplified spontaneous emission effects caused by the high gain of the amplifier, an aperture plate consisting holes of 1.25 mm diameter for each pass was placed 10 cm from the mirror pair.

The gain element is a 1% doped Yb:YLF crystal of 1.0 cm length bonded to a 0.3 cm long undoped YLF endcap. A dichroic mirror is coated directly onto the endcap with >99% reflectivity at 995 nm and 5% reflectivity at 960 nm; the opposing face of the gain element is AR coated at both wavelengths. No endcap was bonded to the AR side of the gain element since the pump is not injected from this side, and, therefore, the thermal dissipation is low compared with the other side of the gain element. The gain element is a-cut with the signal light polarized along the c-axis. The gain element is attached using indium to the cold plate of a liquid nitrogen cryostat for cooling with the crystal oriented such that the c-axis is normal to the cold plate. At the 50 cm focal length lens, the separation between passes is 0.25 cm, and the number of passes is varied between 6 and 14 simply by translating the pick-off mirror. The dichroic mirror and the mirror pair used to fold the optical path are each located 50 cm from the lens. The pump light is directed through the dichroic mirror and comes from a fiber-coupled diode array with an output fiber of 400 micron diameter and 0.22 NA. The pump fiber output is magnified by 3 so that it is 0.12 cm diameter at the gain element. We estimate that approximately 80% of the...
pump light that transmits through the dichroic is absorbed in the Yb:YLF. The amplified signal beam has a waist at the YLF and has a Gaussian beam radius of 0.05 cm at that point. The output of the diode laser is amplified to approximately 1 W cw power by a tapered semiconductor amplifier and fiber coupled. The fiber-coupled amplified signal is carved into 1 µs long pulses at 40 kHz pulse repetition frequency using a combination of an acousto-optic modulator and a LiNbO3 electro-optic modulator specified to provide better than 50 dB extinction in the time between pulses. The modulators were separately measured to provide >29 dB extinction. The pulses are nominally flat-top in time. The signal passes first through the acousto-optic modulator to reduce the average power to the point that it was sufficiently low for the electro-optic modulator. The average input power to the multipass amplifier is 2.6 mW.

No detailed modeling or simulations of the multipass amplifier performance were made. However, a simple, back-of-the-envelope calculation based on previous laser experiments can provide guidance and insight. From previous experiments in a laser oscillator [24], 40 W of output power were obtained from 70 W of pump power at 5.4 dB round-trip (2 passes), large-signal gain. Given the pulse repetition frequencies in the two experiments, from an average energetics point-of-view, the amplifier and oscillator can both be represented well by the cw case. In this earlier demonstration, the pump beam diameter was slightly larger at 1.3 mm diameter compared with 1.2 mm diameter here. Adjusting for the difference in beam diameter, it should be possible to obtain 40 W of output power from 70 W of pump power at a large-signal gain of 44.7 dB using 14 passes, which is a reasonable match with the 43-dB large-signal gain obtained here.

III. RESULTS

Fig. 2 shows the output average power at 995 nm as a function of incident pump power at 960 nm on the dichroic mirror and number of passes. Because of the high gain of this cryogenic amplifier, up to 43 dB large-signal gain, there is efficient extraction even at just a few passes. Over 50% efficiency is achieved at 40 W output power. The saturation intensity and fluence at 995 nm in Yb:YLF at 80 K are 2.4 kW/cm² and 5.0 J/cm² respectively [20], and the average output intensity is well above the saturation intensity consistent with the efficient extraction.

Fig. 3 shows the output pulse shape for 6 and 14 passes at 1 mJ/pulse output energy. In multipass amplifiers, pulse shaping effects tend to be muted, particularly for near Gaussian pulses [25]. Pulse shaping effects are much more noticeable for flat-top pulses and are larger for more passes, as the effective saturation fluence is equal to the saturation fluence divided by the number of passes [26]. This effect, in combination with the more efficient extraction with larger number of passes, accounts for the larger droop in power over the pulse for 14 passes.

The initial spike observed in the output pulse is a result of the finite propagation time through the multipass amplifier, which means that there is only signal power from the first passes within the gain element at the leading edge of the pulse, and consequently, the leading edge sees larger saturated gain than at later times when there is power from all of the passes simultaneously in the gain element. This effect is particularly evident with the waveform used here because the rise time of the pulse, around 1 ns, is much shorter than the propagation time between double passes, around 6 ns, and the length of the pulse is much greater than the total propagation time through the amplifier. The trailing tail on the output pulse is present on the input pulse and is simply a result of the electronics driving the modulator. Given the time between pulses (24 µs) and a nominal trailing tail lifetime of 0.5 µs, the integrated energy in the tail is small compared with the total energy in the 1 µs pulse.

There are no signs of thermo-optic effects, as the quantum defect is small and the thermo-optic properties are excellent at cryogenic temperature. We estimate that the beam quality is about $M^2 = 1.2$. This estimate is based on a measurement of the $M^2$ obtained from the 1/e² diameter from a focusing lens fit to a hyperbola. This measurement was done at similar average power, but a somewhat different temporal waveform. With the different waveform, no qualitative difference was observed in the beam pattern. We believe that further scaling of the output power could be obtained by increasing the pump power without adverse thermo-optic effects, given our previous results of 150 W output power from a Q-switched oscillator in which minimal thermal effects were observed [24].
Fig. 3. Output peak power with 6 and 14 passes at 40 W average output power (1 mJ/pulse).

REFERENCES


