23-dB Ho:YLF Amplifier

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Abstract: Single-stage, 2050-nm Ho:YLF amplifier providing up to 23 dB gain and up to 41% extraction efficiency with high-repetition rate, nanosecond-pulsed, broadband or single-frequency seed is reported.

OCIS codes: (140.3280) Laser amplifiers; (140.3070) Infrared and far-infrared lasers

Efficient and compact single-frequency laser sources operating at eye-safe wavelengths are of particular importance for various applications (e.g. remote sensing). Master oscillator-power amplifier architecture is an attractive approach for construction of such laser sources. A low-power laser oscillator is used as a seed source defining the wavelength, linewidth and pulse format. High gain/high power amplifier stage is used to scale the seed source output to the desired levels. Provided that the required pulse energies are sufficiently low and spectral width of the seed is broad, high-gain fiber amplifiers are usually considered as a preferred option. However, amplification of pulsed, single-frequency signals in fibers constitutes a significant challenge due to such non-linear effects as stimulated Brillouin and Raman scattering.

The goal of this particular effort was to study the feasibility of Ho-bulk laser materials for high-gain amplification of nanosecond pulses with single-frequency linewidth at kHz-repetition rate. Analysis of the laser properties of rare-earth ions [1] shows that most of the laser transitions in the eye-safe wavelength region have such a low gain cross-section that efficient, high-energy laser oscillation or amplification in a bulk laser medium is impossible. Only Ho-doped crystals, including Ho:YAG or Ho:YLF, have a large enough gain cross-section for efficient high-gain operation.

We have chosen Ho:YLF as the gain medium for our experiments because of the combination of a high gain cross section (~ two times higher than in Ho:YAG) and long storage time of the Ho-transition and the athermal and birefringent nature of the YLF crystal, all advantages compared to Ho:YAG and other Ho-doped gain media.

As a pump source for the Ho:YLF amplifier, we utilized a commercially available ~25-W Tm-fiber laser (IPG Photonics) which was wavelength-adjusted to the strongest Ho:YLF absorption line at 1940 nm. Recent progress in the development and commercialization of Tm-fiber lasers providing high CW output power (100s of Watts), diffraction limited beam quality, and wide operating wavelength range, makes these lasers ideal sources for resonant pumping of Ho-doped lasers. Tm-fiber lasers can be wavelength-tuned to match any Ho-doped laser material with the most common being Ho:YAG, and Ho:YLF. Tm-fiber lasers seem to be a preferred alternative to bulk Tm-doped lasers for pumping applications demanding diffraction-limited CW power greater than 25-50 W.

The schematic of Ho:YLF amplifier set-up with longitudinal pumping scheme is shown in Fig.1. Compact, single-crystal Ho:YLF gain module was pumped from one side by a Tm-fiber laser producing collimated, linearly-polarized, diffraction-limited beam at 1940 nm with less than 2-nm linewidth. Maximum pump power from the Tm-fiber laser was ~26 W. Ho:YLF crystal mount was temperature controlled using a single TE-element. The hot side of the TE-element was set in contact with an air-cooled baseplate. No water cooling was used in the amplifier assembly. All Ho:YLF crystals used in experiments had 0.5% Ho-concentration. Ho-amplifier could be configured for single- or double-pass operation.

A low-power, singly-doped Ho:YLF oscillator was used as a seed source. This oscillator could be operated in CW or Q-switched regimes with average output power of up to 1 W. In Q-switched regime the oscillator produced 200-400-ns pulses at 1-10 kHz repetition rate. Single-frequency regime was achieved by installing a pair of etalons in the laser cavity and operating the laser not far from the threshold. Single-frequency operation was verified observing the interference pattern after an external etalon. A variable attenuator allowed continuous adjustment of the seed power incident on the amplifier from 10 mW to ~1000 mW. A single Faraday isolator was used for two purposes: 1) to prevent any feedback from the amplifier, and 2) to allow double-pass operation of the Ho-amplifier. A single spherical lens was used to focus the seed beam into the amplifier. In order to arrange 2-pass amplifier operation the output after the 1st pass was back-reflected using a concave high reflector mirror. The distance between the HR mirror and Ho:YLF crystal (approximately equal to the radius of curvature of the HR mirror) was optimized so that the reflected beam is re-imaged to match the gain region in the crystal.

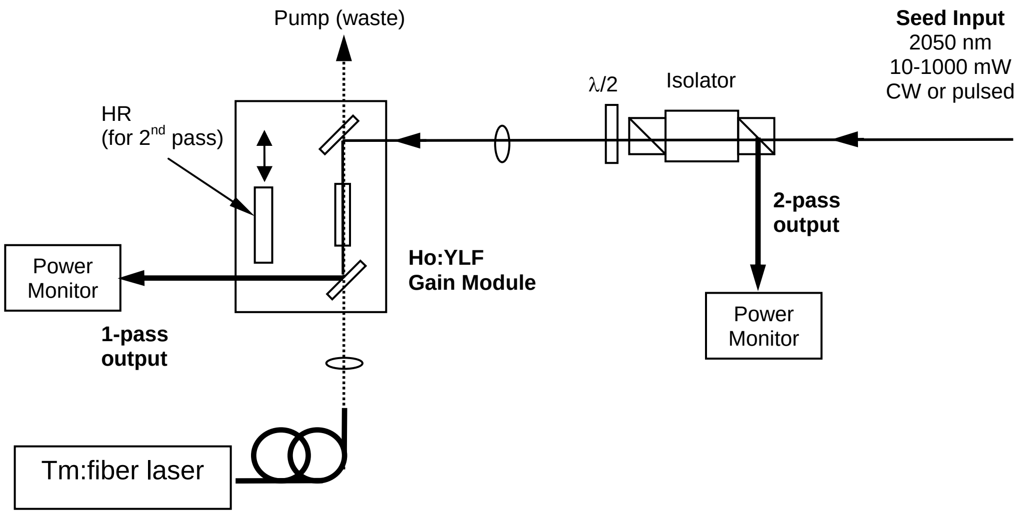


Fig. 1. Schematic layout of the end-pumped Ho:YLF amplifier.

Ho-amplifier performance was characterized in both single- and double-pass configurations. Dependence of the output power, extracted power and gain for Ho:YLF amplifier operated in single- and double-pass regime vs seed power is shown in Fig. 2. Measured beam profiles for the incident seed beam and double-pass amplified output beam are shown in Fig. 3.

Our experiments with bulk Ho:YLF amplifier demonstrated ~10.6 W average-power output with 26-W pump power corresponding to ~41% extraction efficiency. With small signal seed (~10 mW) a double-pass Ho:YLF amplifier exhibited up to 23 dB gain, however, the extraction efficiency (as referred to the amplifier pump power) is lower (~8%). We estimate that up to ~13.5-15 W can be generated in 2-pass configuration with the extraction efficiency of up to 45-50% for the seed power 1-2 W using ~30-W Tm:fiber pump.

Due to long lifetime (~15 ms) of the upper laser level in Ho:YLF, amplification of pulse trains at repetition rate exceeding 1 kHz results in average power output close to CW regime. When the CW-pumped Ho:YLF amplifier was seeded with a pulse train having repetition rate of 2 kHz or above, the observed Ho-amplifier average-power output was almost the same as with a CW seed (provided that the seed average power was kept the same). Maximum average power of ~10.6 W demonstrated in our experiments was enough to produce >2 mJ at up to ~5 kHz repetition rate. We estimate that in our particular set-up the limit on the maximum pulse energy set by the optics damage threshold is exceeding 10 mJ.

The amplifier output was practically independent on the bandwidth of the seed laser: similar output was observed with broadband or single-frequency input. Given the nature of the bulk crystal amplifiers, they provide damage-free operation and are immune to nonlinear effects such as Brillouin and Raman scattering which adversely affect the amplification of single-frequency seed sources in fiber amplifiers.

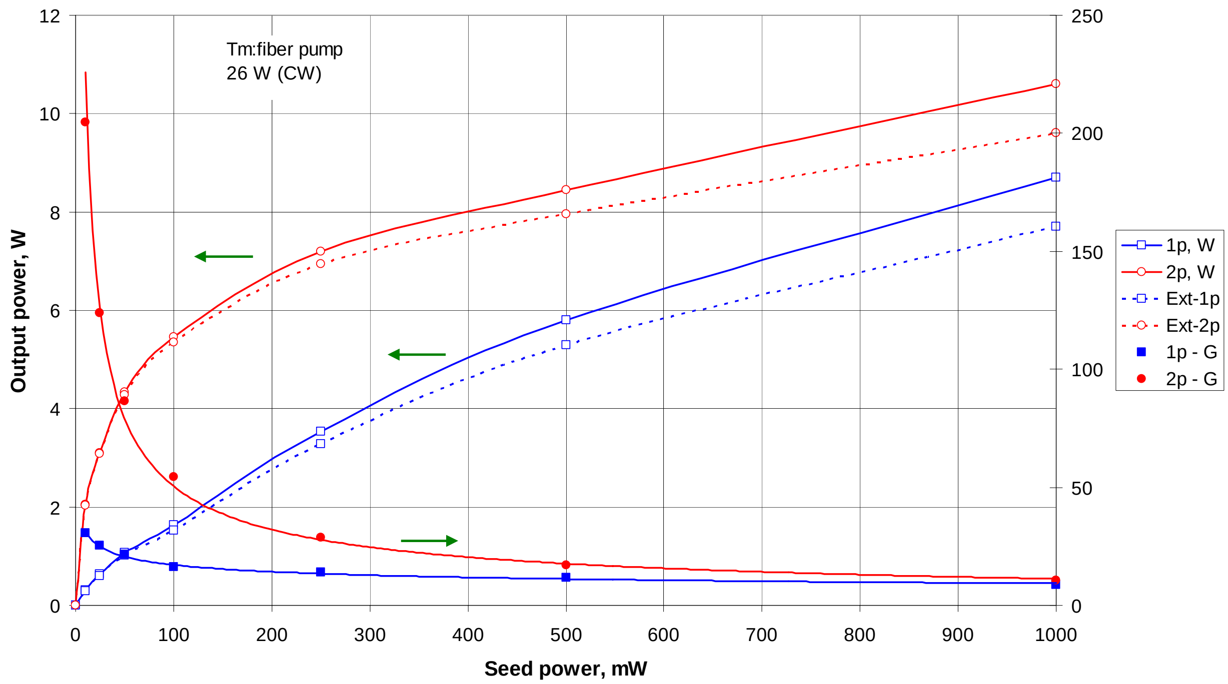
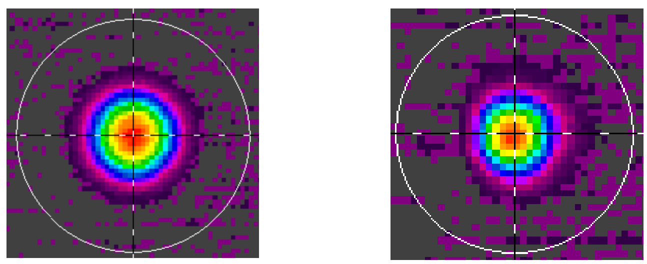


Fig. 2. Ho:YLF amplifier output power, extracted power and gain for single- and double-pass operation vs seed power (Squares – 1-pass data, Circles – 2-pass data; dashed lines correspond to extracted power)



a) Input (seed osc beam) b) Output (2nd pass)

Fig. 3. Beam profiles for a) Seed oscillator, and b) amplifier output in double-pass operation

In conclusion, double-pass Ho:YLF amplifier demonstrated gain of ~ 23 dB (comparable with that of Tm:fiber amplifiers) and up to 41% extraction efficiency. Key advantages of a bulk Ho:YLF amplifier as compared to Tm:fiber amplifiers are: 1) ability to generate high pulse energy, 2) immunity to such deleterious effects as stimulated Brillouin and Raman scattering which limit the performance of fiber amplifiers, and 3) damage-free operation.

References

[1] S.A. Payne, L.L. Chase, L.K. Smith, W.L. Kway and W.F. Krupke, IEEE J. Quantum Electron. 28, 2619 (1992)