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High power cryogenic Ho:YAG laser

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Abstract: We have improved significantly the brightness of cryogenic Ho:YAG, reporting up to 65 W output power with a beam quality of $M^2 < 1.3$ and a slope efficiency of 71%. The laser emission was ~ 2 nm wide and centered at 2097.5 nm. This result demonstrates the scalability of both the narrow-line thulium fibre pump laser and the cryogenic laser head.

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1. Introduction

High power, high energy sources operating at $\sim 2\ \mu\text{m}$ are of interest in applications such as LIDAR, defence and material processing and as pump sources for non-linear frequency conversion to enable high energy mid-IR sources [1, 2].

Common laser materials in this wavelength regime, such as Ho:YLF and Ho:YAG are quasi 3-level at room temperature (RT) and thus require high pump intensities, leading to optical distortions, possible optical damage and limitations on the maximum pulse energy achievable. Subject to these limitations, significant progress of Ho-based RT lasers has still been achieved with average powers in excess of 100 W having been demonstrated using multiple gain media and MOPA configurations [2, 3]. Such approaches add complexity and impose restrictions on further power scaling. However, cryogenic cooling (CC) of quasi 3-level gain media greatly reduces the thermal population in the lower energy levels, thus approaching 4-level laser operation [4–7] and significantly reducing the laser threshold.

Early work reported a cryogenically cooled Ho:YAG laser for medical applications demonstrating near 4-level lasing at up to 50W, but the laser was lamp pumped, required pre-cooled liquid oxygen and had low efficiency [4]; furthermore no spectroscopy or beam quality was reported. Comparing more recent results at RT [3, 8–10] with those at cryogenic temperatures (CT) [5, 11, 12] demonstrates the substantial differences in threshold. In particular, the lowering of the laser threshold at CT allows for a lower pump intensity, thus enabling a larger laser mode volume to be exploited, while maintaining overall efficiency.

While dramatic improvements and subsequent power scaling have been predicted and achieved for the CC of quasi 3-level lasers using Yb^{3+} in YAG and other hosts [13–15, 20], equivalent improvements are yet to be demonstrated in a Ho:YAG laser system. Mackenzie et al. reported a LN_2 cooled Ho:YAG laser pumped by a thulium-doped fibre laser (TDFL) at 1932 nm producing ~ 15 W with a slope efficiency of 49% [5]. Cryogenic lasing in Ho:YLF [16] and Ho:YVO₄ [17] have also shown improvements, but the increases in output power as a function of pump power for these demonstrations appear to saturate at power levels less than 10 W and the beam quality observed is limited, even at modest output powers. The problems encountered are due in part to the narrow absorption line-width at cryogenic temperature [4–6] and in part to issues with the thermal management of the gain medium.

Our present work seeks to address these issues and demonstrate the scalability of the CC of Ho:YAG lasers using liquid nitrogen (LN_2). In the work reported in [12] we presented the possibility of lasing using the absorption bands of Ho:YAG at 1907 nm and 1908 nm at cryogenic temperatures. These bands are narrow, but have high absorption coefficients. Efficient pumping thus requires narrow line-width pump lasers, which can be provided by accurately tuned, thulium fibre lasers. Such lasers have been demonstrated to have excellent beam quality at high output power of >100 W at the wavelength required for the present purpose [18, 19].

Here, we present a high power, cryogenically cooled, continuous wave (CW) Ho:YAG laser. We use our previously described design for the cryogenic laser head [20], resulting in negligible mechanical stress or strain distortions in the laser crystal when cooled and pumped, while providing uniform cooling and heat dissipation. By matching the pump laser emission to the measured narrow absorption features, we achieve a maximum slope efficiency of 74% at output powers up to 80 W for a multimode resonator and a 71% slope efficiency with an output power of 65 W with good beam quality ($M^2 < 1.3$) using simple resonator

configurations and requiring no thermal compensation. We report on the scalability of our laser design and performance of the laser system.

2. Cryogenic laser design

Ho:YAG was selected as the gain medium based on our previous results and the availability of suitable high power pump lasers. To achieve the maximum benefits of cryogenic cooling of the YAG host, the dopant concentration of Ho^{3+} must be kept low, thereby promoting an end-pumped configuration with a long absorption length and large cooling surfaces [12]. The thulium fibre pump laser must provide high power in a narrow line-width with excellent wavelength stability and beam quality suitable for mode-matched end-pumping of the laser crystal.

2.1 Thulium fibre pump laser

The spectral widths of the Ho:YAG absorption lines in the 1905-1911 nm region are approximately 0.3 nm [12], which compares favorably with the <0.15 nm line-width of the high power TDFLs used [21, 22]. Both the 1907 nm and 1908 nm absorption strengths are high and not influenced by atmospheric water absorption.

Here we report only the results of the laser performance when pumped by a 1907 nm TDFL, but we also obtained very similar results when pumping at 1908 nm. The pump laser was measured to have a diffraction limited beam quality ($M^2 < 1.05$) and excellent pointing stability at all operating powers. The wavelength of the laser was defined by fibre Bragg gratings (FBG) [22] and was accurately tuned by controlling the temperature of the FBG's in the laser cavity. Figure 1 shows the typical spectra of the TDFL over a range of output powers. The TDFL was terminated using a slightly angled, bulk 10 x 10 x 10 mm, anti-reflection (AR) coated Infrasil endcap attached using CO_2 laser processing. The bulk end-cap reduced back-reflections into the laser cavity and simplified the mounting and collimation of the fibre laser output.

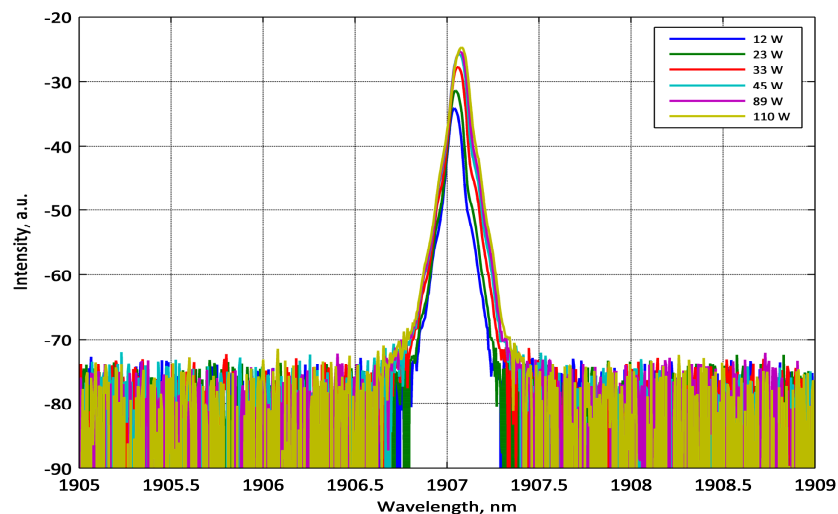


Fig. 1. Emission spectra of the 1907 nm thulium fibre pump laser, demonstrating narrow emission bandwidth (<0.1 nm) and wavelength stability (<0.07 nm) as a function of output power up to 110 W.

2.2 Ho:YAG gain medium, thermal behavior

The laser head used was similar to that described in [20]. The laser crystal was a 2 x 3 x 49 mm, 0.3% at. Ho:YAG straight-through slab with end faces AR coated for 1907- 1908 and 2097 nm.

The thermo-optical properties of the cooled and pumped gain medium were investigated separately using a Mach-Zehnder interferometer with a 632.8 nm HeNe laser beam co-axial with the pump laser and the eventual lasing mode. The resulting interferograms are shown in Fig. 2. The first three images show some slight imperfections in the laser crystal, but no cryo-mechanical stress of the cooled slab with no pumping. The slab was subsequently pumped using a 1907 nm thulium fibre laser that was wavelength tuned to maximize the absorption of pump power in the crystal. No significant pump-induced stress was observed at pump power levels up to 90 W with a beam diameter of 0.9 mm. This resulted in ~60 W of absorbed pump power, which corresponds to the typical heat load expected when lasing at about 200 W, assuming the ~70% slope efficiency typically achieved with a Ho:YAG laser oscillator.

These observations of minimal wave-front distortions at high thermal load demonstrate the excellence of our cryogenic laser head design and the potential for further power scaling of cryogenic Ho:YAG. Note that the interferometer images were taken using a HeNe laser at 632.8 nm and indicate correspondingly smaller distortions at the operating wavelength of 2097 nm.

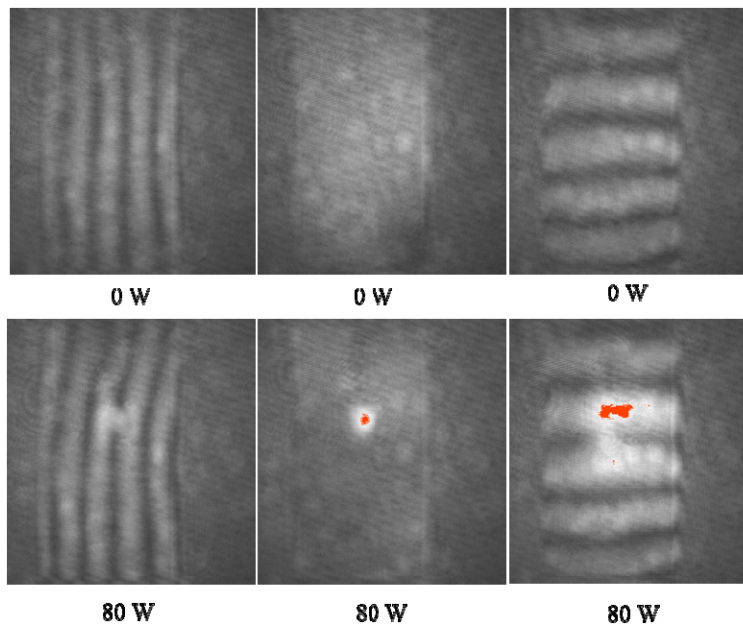


Fig. 2. Interferograms of the full aperture of the Ho:YAG crystal at 77 K. Top row shows vertical, zero and horizontal carrier fringes at 0 W of pump power. The bottom row is similar, but with 80 W of pump power and no lasing. The exact origin of the bright red spot has not been determined. It occurs without the HeNe laser and is not related to the interferometry. It is presumed to be a non-linear emission at a wavelength shorter than the pump.

3. Cryogenic Ho:YAG laser performance

The optical layout of the laser is shown in Fig. 3. The schematic includes the vacuum envelope of the cryostat, the windows through which the pump and laser beams pass and the laser resonator formed by mirrors M_1 and M_2 . The resonator mirrors were separated by 800 mm. M_2 was a concave mirror with a radius of curvature of 500 mm, coated for high reflectivity (HR) at the lasing wavelength of 2097 nm. M_1 was the output coupler and three

different configurations for M_1 were investigated using available optics: a 70% reflectivity mirror with a radius of curvature of 500 mm, a 50% reflectivity mirror with a radius of curvature of 500 mm and a combination of a flat 30% reflectivity mirror immediately adjacent to an AR-coated lens with a focal length of 750 mm, this combination effectively acting as a curved mirror, reflectivity 30% and radius of curvature of 750 mm. While the longer radius gave rise to a larger volume of the fundamental mode in the gain medium, we did not vary the pumping optics or the pumped volume.

The pump beam was collimated by an aplanatic lens ($f = 25$ mm) and launched into the laser crystal via a dichroic mirror, D_2 (high transmission (HT) at 1907-1908 nm and HR at 2097 nm). The optical transmission of each cryostat window was measured to be 98.5% at both the pump and laser wavelengths. The pump light reflected from the dichroic D_2 at an angle of 16° was analyzed using an optical spectrum analyzer (OSA) and monitored for pump source wavelength stability. We observed no noticeable variations ($> 1\%$) in any of the pump power, the pump wavelength or the Ho:YAG laser power during several hours of continuous operation.

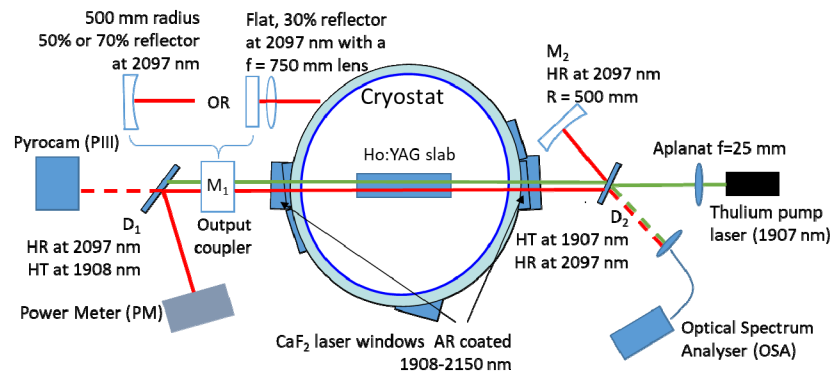


Fig. 3. Schematic of the optical layout of the laser in the cryostat as described in the text, including the external pump laser optics and the diagnostics used. The green lines represent the pump beam path and the red lines the lasing beam path.

Pumping at 1907 nm resulted in high efficiency, low threshold lasing as shown in Fig. 4. The laser threshold was measured to occur at ~ 0.8 W pump power and output powers up to 80 W were demonstrated with a slope efficiency of up to 74%. The efficiency as a function of pump mode size was investigated for the simple resonator with M_1 of radius 500 mm as shown in the inset of Fig. 4. For optimum efficiency the $1/e^2$ mode diameters of the pump and lasing modes were measured to be 0.8 mm and 0.75 mm respectively, consistent with those predicted by a simple ABCD model of the resonator. In each case the output beam appeared to be single mode at low powers and tending towards multi-mode at higher powers. The slope efficiencies were found to increase with decreasing out-coupling reflectivity, ranging from 60% to 74% as shown.

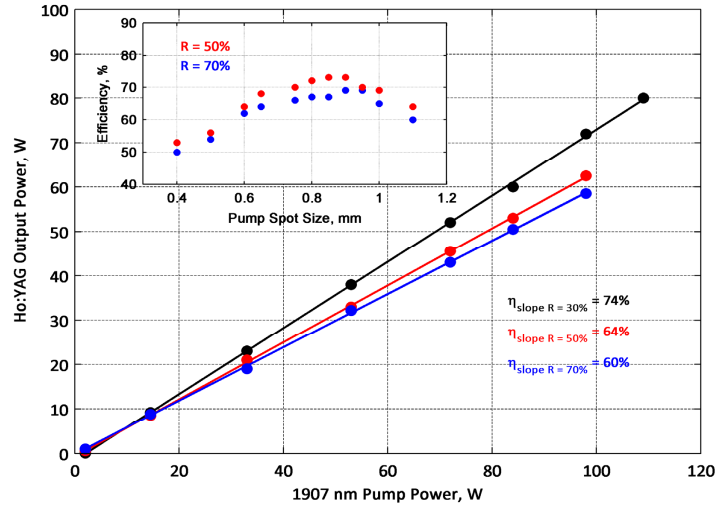


Fig. 4. Output power of the Ho:YAG laser as a function of 1907 nm pump laser power for different output reflectivities and resonator configurations, resulting in slope efficiencies ranging from 60% to 74% as indicated. See text for further information. Inset: Slope efficiency vs. pump spot diameter for the 50% and 70% reflectivity mirrors.

In the final configuration the resonator was aligned in order to achieve the best beam quality at high power. This used the 30% reflectivity mirror and the 750 mm focal length lens as the output coupler M_1 and produced up to 65 W with a slope efficiency of 71% as shown in Fig. 5. The inset in this figure shows the spectrum of the laser output at 65 W. Similar spectra

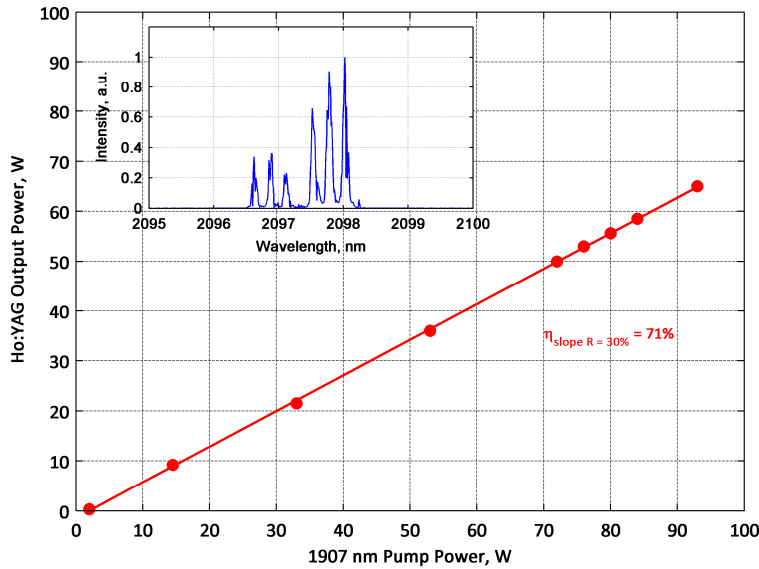


Fig. 5. The slope efficiency and output power of the laser configuration used for the measurements of beam quality in Fig. 5. The inset shows the spectrum of the laser emission at the maximum output power.

were measured at all output power levels and no other spectral components were observed between 2050 nm and 2150 nm. The spacing of most of the smaller peaks in the spectrum

corresponds quantitatively to etalon effects in the cryostat windows. The overall spectral envelope observed is similar to that reported in [3].

The beam quality of the laser was determined by focusing the output beam and measuring the beam profile as a function of distance. An imaging system with a magnification of 5.0X was used for the camera to resolve the beam diameter near the waist. The corresponding measured radii, curves of best fit and images of the near and far field profiles are shown in Fig. 6.

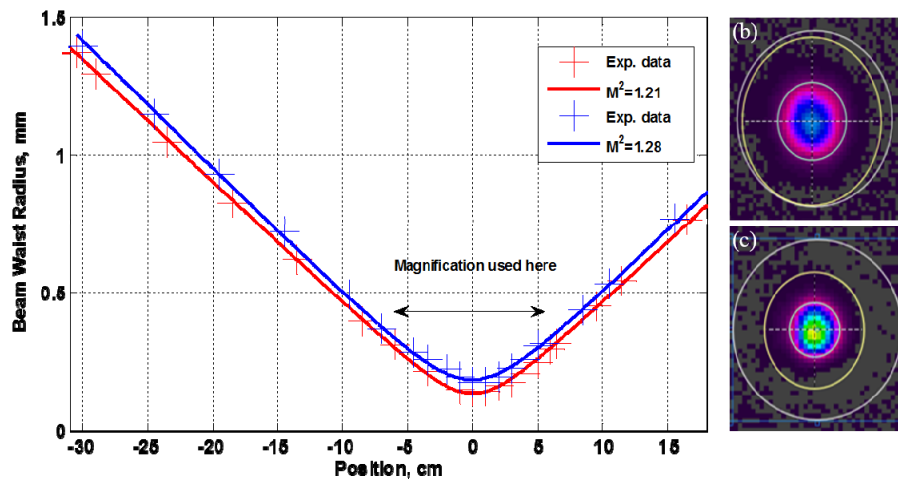


Fig. 6. (a) Beam radius measurements through the focus of the laser beam at 65 W output and lines of best fit corresponding to an $M^2_{x,y} = 1.21, 1.28$. (b) Near-field profile of the Ho:YAG output at 65 W. (c) Far-field profile of the Ho:YAG laser output at 65 W viewed with an imaging system with a magnification of 5.0X.

4. Summary and conclusion

We have investigated and characterized a cryogenic slab Ho:YAG laser head pumped by a TDFL, tuned for maximum absorption efficiency in CC Ho:YAG. The combination of two key factors, the scalability of the narrow line-width pump source and the scalability of the laser head, resulted in laser operation with a low threshold, high output power, high slope efficiency and near diffraction limited beam quality. We have thus achieved up to 80 W cw, but characterized the laser in detail at an output power of 65 W, lasing at 2096 – 2098 nm with good beam quality ($M^2 < 1.3$).

Our results represent a significant improvement in the efficiency, average power, beam quality and thus brightness of cryogenic Ho:YAG lasers. Neither the laser head nor the 1907 nm TDFL pump source showed degradation over months of daily work, indicating that further power scaling is feasible. Future efforts will focus on improving the resonator design, understanding and controlling the spectrum of the emission and further power scaling.

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