Influence of intracavity-air loss on 946-nm Nd:YAG laser performance

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Abstract

We report on the impact of humidity in a cryogenically cooled Nd:YAG laser operating at 946-nm. Performance degrades with increasing cavity length, which is attributed to absorption by water vapour, an additional intracavity loss.

1. Introduction

Diode-pumped neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers operating at 946-nm on the $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition have been studied since the late 80's [1, 2]. Notwithstanding their subsequent development, the performance of these lasers has continued to be inferior to the more common 1-μm Nd:YAG laser. This is generally attributed to ground state reabsorption losses and relative low gain for the 946-nm transition that competes with the stronger 1-μm emission. Consequently, performance of these lasers is very sensitive to the intra-cavity losses.

In-band pumping of Nd:YAG whilst operating on the $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition is akin to the 2-level energy scheme of Yb-doped gain media. Furthermore, cryogenically cooling this gain medium practically eliminates reabsorption involving thermally populated Stark levels, resulting in a 'four-level' system with potential for high efficiency and comparable quantum defect to Yb^{3+}-laser systems [3, 4]. The latter report [4], was about a short-cavity cryogenically cooled Nd:YAG laser that produced over 110W at 946-nm with a slope efficiency of 80%. Notably, most of the cavity length for that system was within a vacuum surrounding the laser crystal, utilised for thermal isolation. We've observed that longer cavities, designed to improve mode matching between the pump and laser fields, suffer a dramatic drop in efficiency, with modal instabilities appearing at moderate powers, seemingly linked to thermal effects in the laser cavity [3]. Here we report on the influence of an uncontrolled laboratory atmosphere, namely the relative humidity, on the performance of a cryogenically cooled Nd:YAG laser operating at 946 nm. The implications extend to all lasers that suffer non-negligible absorption in air.

2. Experimental setup

Intracavity losses derive from energy transfer between photons and matter, typically attributed to interactions with solids, such as the gain medium or optical components. Water vapour in air, is known to absorb at certain wavelength bands that overlap with solid-state-laser transitions, e.g., absorbance around 946-nm, calculated using the HITRAN2020 database [5], is shown in Fig. 1. Moreover, for high-power-laser propagation through atmosphere, thermal blooming is known to distort the wavefronts and irradiance distribution at the target [6]. To investigate the potential effects of the humidity on the 946-nm laser performance, a 'V-cavity' was configured to allow a variety of cavity lengths without significant change to the mode overlap in the gain medium, Fig. 1.

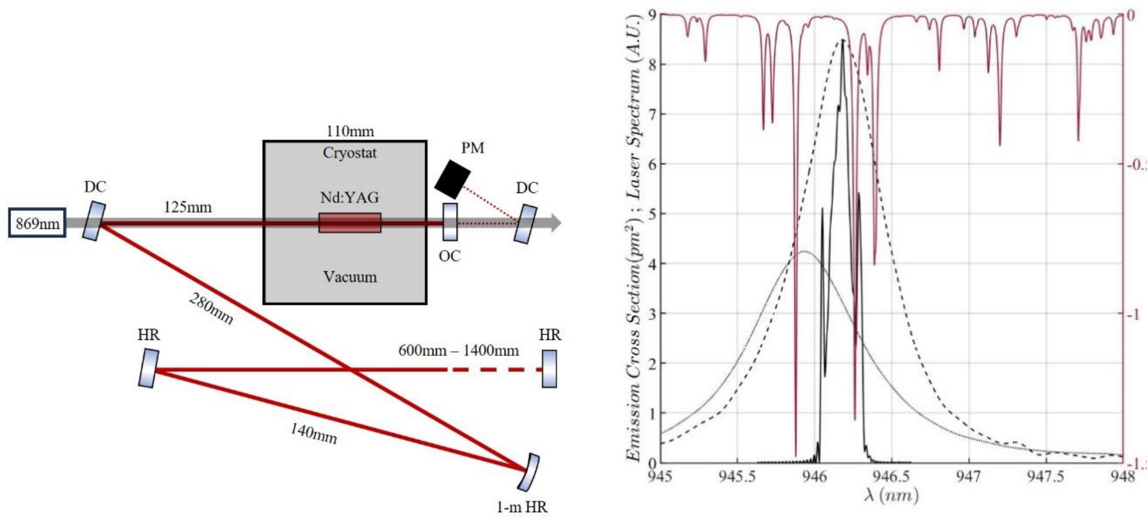

Fig.1: (left) Laser setup, DC - dichroic mirror, 1-m-radius curved mirror, HR - high-reflector, OC - output-coupler, PM - power meter; (right) comparison of Nd:YAG emission cross sections at 300K (black dotted) and 80K (black dash), and lasing spectrum (black solid), to the calculated absorption of water vapour [5] (red solid) at 296K and 45% relative humidity.

The 869-nm diode-pump source has been previously detailed in [3], altered to have temperature control of the volume Bragg grating to fine tune the pump wavelength, and focused beam waist parameters (W_x=(190+/-5) μm, M_x^2=20+/-1, W_y=(240+/-50) μm, M_y^2=12-25). Instead the closed-loop cryostat configuration was presented in [4]. Through extension of the near-collimated section of the V-cavity, the path length in air could be varied from ~1150 mm to ~1950 mm, for an overall cavity length of 1250-2050 mm, with a modelled cavity-mode radius in the 15-mm-long 0.3-at.% Nd:YAG crystal equal to ~190 μm. The cavity mode was monitored by 1-to-1 reimaging the end HR mirror onto a Spiricon CCD camera, characterised via the associated BeamGage software.

3. Results

An emission spectrum for the cryogenically cooled 946nm Nd:YAG laser is plotted against water vapour absorption lines, Fig. 1, illustrating a coincident absorption feature and spectral dip, indicating intracavity absorption is limiting the gain bandwidth associated with the emission cross section. Threshold measurements plotted for a 'Findlay-Clay' loss analysis, Fig. 2, provide calculated cavity loss from 2.4% to 4.1% with increasing cavity length, from 1400mm to 2000mm, respectively. However, owing to the fluctuating relative humidity (RH), between 30% to 57%, it is evident that intracavity loss is directly influenced, which in turn adds significant uncertainty to the Findlay-Clay analysis. Nevertheless, for all OC values, increasing cavity length increases the laser threshold, P_{th}, implying higher loss. Additionally, the laser slope efficiency for two cavity lengths, operating in an ambient 41% to 43% RH environment, is shown in Fig. 2, whence diminished slope efficiency and exacerbated power rollover are evident for the longer cavity. Cavity mode radii at the HR end mirror were reimaged to a CCD-array and logged simultaneously with output power curves demonstrating a growth with increasing output power, Fig. 2. Whereas cavity modelling showed relative constancy around 1mm in function of power, Fig. 2. There is a strong divergence between the measured and simulated mode size, whereby the observed mode-radius growth for cavities of 1250mm and 1850mm length, is attributed to the thermal blooming associated with heating of humid intracavity air. Example mode-profile insets in Fig. 2, illustrate their evolution with power.

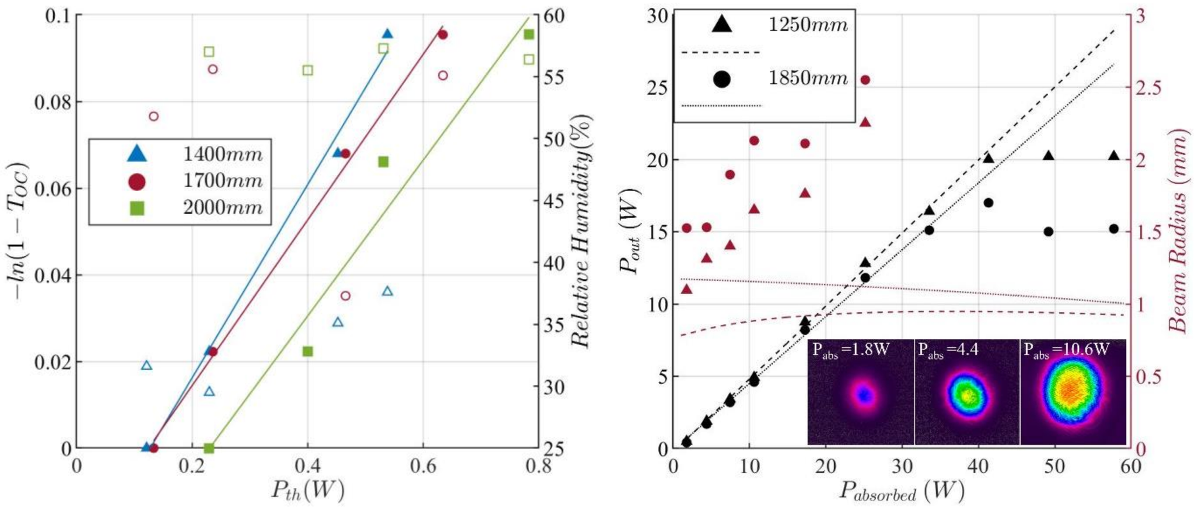

Fig.2: (left) Findlay-Clay threshold measurements (closed symbols – power; open symbols – RH%); (right) laser performance for two cavity lengths, calculated and imaged mode size at the flat cavity end-mirror. Inset images example beam profiles at specific pump powers.

4. Conclusions

Progressive deterioration of 946-nm laser performance is reported for increasing cavity length in humid laboratory conditions. Though potentially obvious, holistically our experimental results provide evidence for the deleterious influence of intracavity humidity on lasers operating at wavelengths that suffer absorption by water-vapour, or by extension other gas species. These results may explain the historical lack of efficient 946-nm laser systems.

5. References

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