Dynamically stable continuous single frequency green ring laser

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Abstract— **A single-frequency ring laser using two standard commercial diode-pumped Nd:YAG modules is demonstrated. Employing a dynamically stable resonator design, multi-longitudinal mode operation at 1064 nm with 53 W of output power was obtained. When inserting a LBO crystal in the resonator, 1.8 W of single-sided, single-frequency output at 532 nm was achieved. The measured linewidth was 3.6 MHz, close to the resolution limit of the scanning etalon used to measure the longitudinal mode structure.**

Keywords—Single frequency lasers, ring lasers, dynamic stable resonators, second harmonic generation

I. INTRODUCTION

Ring resonators are suitable for obtaining stable, narrow linewidth, unidirectional single-frequency lasers. Single-frequency is required for external enhancement cavities, which present the highest known conversion efficiencies in frequency doubling, and also present extremely small linewidth, many orders of magnitude smaller than the gain linewidth, as necessary for high-resolution spectroscopy and laser deceleration [1]. Among the advantages of ring laser resonators is the wider stability interval that allows larger beam waists at the laser crystal position when compared to standing-wave resonators [2]. Most of the ring lasers described in the literature make use of longitudinal pumping schemes and do not take advantage of the wider stability zone provided by ring resonators. This not only makes the resonator more prone to instabilities caused by changes of the thermally induced focal length, but also limits the maximum extractable output power. Our design goal is a ring resonator with the capability for very high single-frequency green output power. In this work we establish a roadmap for such a resonator and demonstrate its first step, which is a single-frequency polarized ring-cavity with initial results of second harmonic generation (SHG).

Laser output power is proportional to the volume of the pumped active media that overlaps with the laser beam inside the crystal. A large stationary beam waist inside the gain media is therefore desirable. The dynamically stable resonator design techniques developed by Magni [3] allow for configuring the stationary beam waist inside the laser rod, w_{30}, as large as necessary given that diffraction at the rod aperture is the limiting factor. To maintain a large mode volume and minimize at the same time the associated diffraction losses caused by clipping at the rod, w_{30} must be in the range of 50%-83% of the rod radius.

For Nd:YAG gain media, with its inherent thermally induced birefringence, polarizing the laser output causes depolarization losses and the associated thermally induced bifocal lens sets limits the maximum achievable stationary beam waist inside the rod. Because the stability range in terms of dioptric power is inversely proportional to the square of the size of the stationary beam waist inside the rod and considering the fact that the ratio of tangential to radial focusing lengths is 1.2 for Nd:YAG, both polarizations may not be stable at the same time for large w_{30} values, generating an upper limit for the beam waist w_{30} of 1.1 mm [4,5]. One approach to deal with this limit is the use of joined stability zones, which can be done by choosing resonator parameters such that the stability zones are close together, generating a twice as large stability zone and allowing a larger beam waist [6-8]. However, the joined stability zones are not really united and always will present a discontinuity in the middle.

The use of ring resonators shows a more favorable condition with a true single, continuous, twice as wide stability zone. Silvestri, Laporta and Magni [2] demonstrated that the stability diagram of a ring laser with a focusing rod always exhibits a single stability zone whose width in terms of dioptric power is twice that of a standing wave resonator. This capability is especially desirable in the case of side-pumped Nd:YAG, where strong induced birefringence leads to a large separation of the radial and tangential thermally induced lenses which may easily exceed the range of dioptric powers over which the resonator is stable, not allowing for the oscillation of both polarizations simultaneously.

Additionally, the use of known birefringence compensation techniques [9,10] may be useful to mitigate the effects of bifocusing and depolarization losses. Also, a polarized laser beam is important in many applications such as SHG and cannot automatically be achieved as when using birefringent crystals [11,12, 13, 14]. In this work a half wave plate (HWP) was inserted in between two identical laser modules to compensate for thermally induced birefringence.

II. EXPERIMENTAL SETUP

The diode pump modules (DPL-1064-S1-0075, HTOE Optoelectronics) consisted of a water cooled doped (0.6 at%) Nd:YAG rod of size Ø 3 mm x 78 mm, pumped at 808 nm by 12 diode bars disposed in a three-fold geometry. Three gold plated reflectors directed the pump light back into the rod for a second pass through the crystal in order to increase absorption. Maximum pump power was 225 W per module. Fig. 1 shows the pump scheme of the modules.

The resonator consisted of a symmetric bow-tie resonator as shown in Fig. 2. Mirrors M_1 and M_2 had radius of curvature of 500 mm and mirrors M_3 and M_4 were plane mirrors. M_1, M_2, and M_3 were highly reflective (HR) at 1064 nm and M_4 had 35% transmission at 1064 nm and was replaced by a HR mirror at 1064 nm for SHG. Incidence angle at the mirrors was 5° in order to minimize astigmatism.

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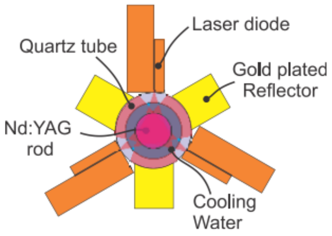

Fig. 1. Diagram displaying a cross-sectional view of the pumping scheme of the laser module.

For SHG a 4x4x20 mm^3 type I non-critical phase matching LBO (Bluebeam optical tech Inc) was inserted in the beam waist between M_1 and the Nd:YAG rod (Fig. 3). The non-optimized crystal surface reflections of the LBO were 6% and 3% per surface at 1064 and 532 nm, respectively. Fig. 3 shows the plot of the beam waist along the resonator axis.

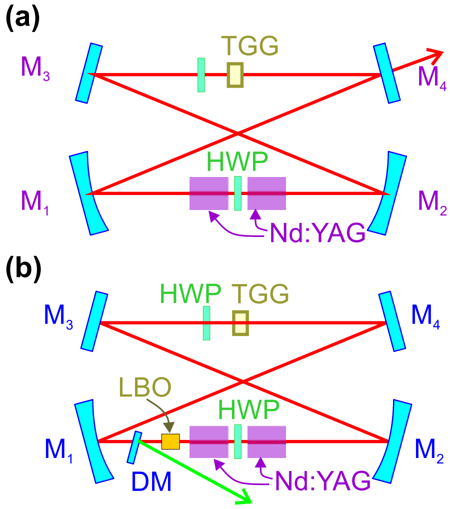

Fig. 2. Resonator scheme for 1064 nm operation (a) and for single-frequency 532 nm operation (b). M_1, M_2, curved mirrors; M_3 plane mirror; M_4 output coupler; HWP half wave plate; DM intracavity dichroic mirror.

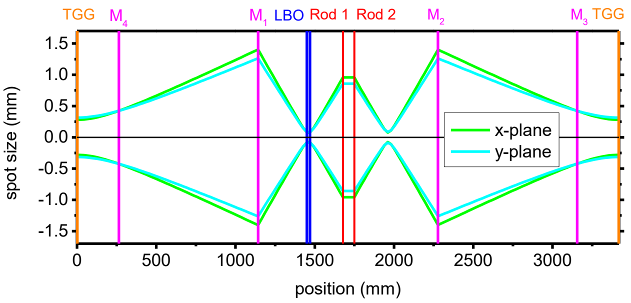

Fig. 3. TEM$_{00}$ spot size along z azis with the laser components written on the top of the graph.

In the absence of a mirror M_4 with HR at 1064 nm and high transmission (HT) at 532 nm, an intracavity mirror with AR at 1064 nm and HR at 532 nm was used to extract the green output as shown in Fig. 2b. For unidirectional operation, a non-reciprocal device composed of a HWP (half-wave-plate) at 1064 nm and a 6 mm long Brewster angle cut terbium gallium garnet (TGG) crystal inside a magnet was inserted between mirrors M_3 and M_4, as shown in Fig. 2, which also worked as a polarizer element.

Longitudinal mode structure was investigated utilizing a 3 MHz resolution *Fabry-Perot* interferometer (Burleigh). The resonator beam waist inside the Nd:YAG rod was simulated using the LasCad$^{@}$ software (Fig. 4).

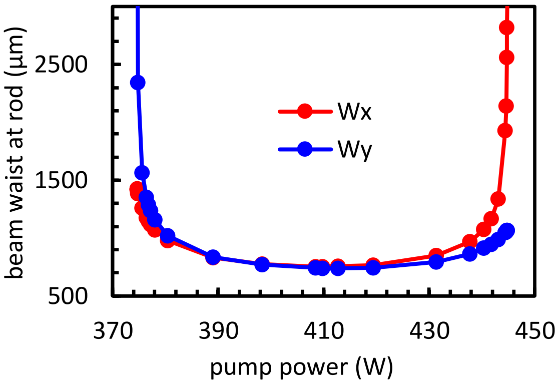

Fig. 4. Simulated beam waist inside rod as a function of diode pump power showing the total dinamic range of the laser and a single stability interval.

III. RESULTS

The laser achieved 80 W of output power at 1064 nm in bidirectional operation. With birefringence compensation, using the polarization rotator between the modules, the output power decreased to 64.6 W but the beam quality factor became much better, from M^2=3.5 to M^2=1.6 [15]. With the TGG and an additional HWP for unidirectional operation, the output power dropped to 51 W as shown in Fig.5. The high laser threshold around 380 W is due to the resonator project which is optimized for high power output and therefore presents a small stability interval and thus small dynamic range.

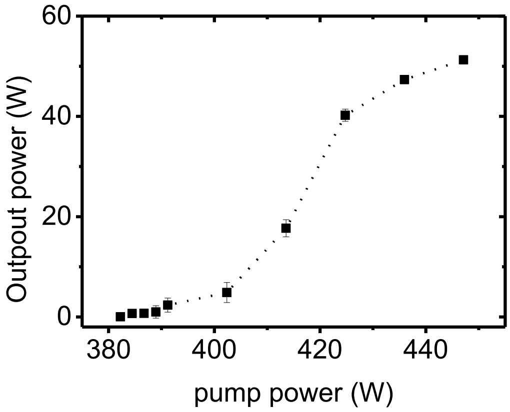

Fig. 5. Uni-directional, high-beam quality (TEM$_{00}$) Laser output power at 1064 nm as a function of pump power supplied by the diodes at 808 nm.

When inserting the LBO crystal inside the resonator, a maximum green output power of 1.8 W was measured. The low performance is credited mainly to the non-optimal reflectivity of the LBO coatings at 1064 nm.

Before introducing the LBO crystal into the cavity, the laser longitudinal mode spectrum presented three peaks with a modulation of 13.5 GHz (See Fig. 6). The LBO crystal improved the spectral output and the reasons are: First, the LBO acted as an etalon due to its relatively high reflectivity coatings, suppressing the adjacent peaks. The second reason was that the nonlinear losses can suppress longitudinal multimode oscillation and mode hopping [16]. When the LBO temperature was adjusted closer to the phase matching temperature the adjacent modes were suppressed as can be seen in Fig. 7. Measured line width was 3.66 MHz, slightly bigger than the etalon resolution of 3 MHz.

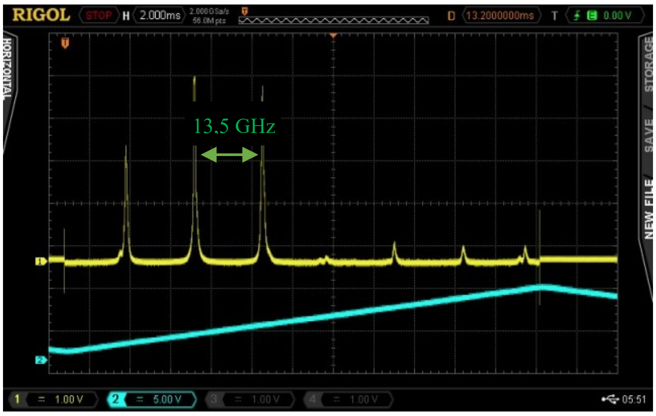

Fig. 6. Laser output spectrum at 1064 nm without LBO.

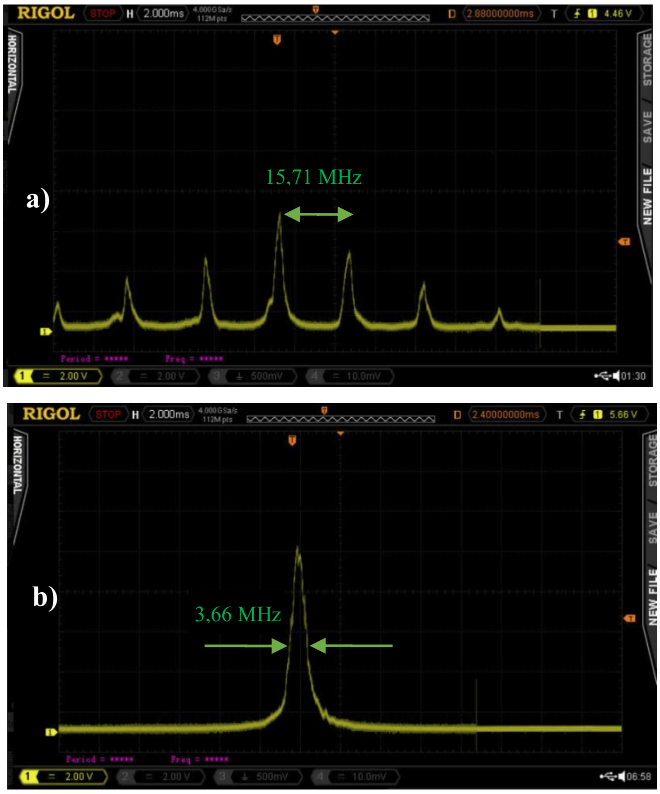

Fig. 7. 1064 nm frequency spectrum obtained with the LBO phase matching temperature detuned (a) and tuned (b) for second harmonic generation.

IV. DISCUSSION AND CONCLUSIONS

A maximum multi-mode output power of 80 W at 1064 nm was achieved in bidirectional operation, which dropped to 65 W when birefringence compensation was adjusted. However, beam quality improved to M^2=1.6, which is close to fundamental mode (TEM_{00}). With the TGG and an additional HWP for unidirectional operation, the output power dropped to 51 W. The insertion of the SHG crystal generated a single-frequency, unidirectional output of 1.8 W, limited by the non-optimal crystal coating.

A maximum single-frequency output power of 35 W at the fundamental wavelength (1064 nm) was achieved when the LBO was slightly detuned. This high single-frequency output power is a demonstration of the success of the strategy mployed here to use a single, large, joint stability zone in the resonator design in order to increase laser stability and single-transverse mode (TEM_{00}) output power.

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