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Dynamically stable operation of a 100-watt level CW single frequency ring laser at 1064 nm

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ABSTRACT

For high-resolution spectroscopy, a stable, narrow linewidth and high power output laser is desirable in order to pump different types of resonant optical parametric oscillators, which is the goal of the present work. Typical single frequency pump lasers are in the range of 10 watt output power whereas, depending on application and OPO type, higher power (>20 W) is desirable. Here we demonstrate a high-power single frequency laser based on off the shelf standard Nd:YAG pump modules. Two closely spaced, diode-side-pumped Nd:YAG rods were used in a mode-filling configuration to form a CW polarized ring resonator with TEM_{00} beam quality and output power of 105 W. The output power achieved is, to our knowledge, the highest reported for continuous polarized, fundamental-mode ring lasers using standard side-pumped Nd:YAG modules. The resonator allowed for power tuning over a large dynamic range and achieved excellent beam quality, using a half wave plate between both rods for birefringence compensation. Single frequency operation was achieved using a TGG crystal and an etalon, with a preliminary output power of 40 W.

Keywords: Laser resonators, Laser optics, neodymium Lasers, solid-state Lasers, pumping.

1. INTRODUCTION

Building robust lasers with high output power and good beam quality with defined and stable spectral output has always been an important goal in laser development. Especially in the range of tens of watts to a few kilowatt of output power, these lasers are employed in an especially wide range of applications that include industrial, medical, science, environmental and free-space communications. When comparing the different classes of lasers, there is an ongoing trend for fiber lasers to substitute solid-state bulk lasers, especially in heavy duty applications, such as industrial, and refined, mostly scientific applications that require spectral and spatial laser beam purity. Yet a simple, reliable and cheap source for linearly polarized, high quality beams remains of interest for a large number of applications. Nd:YAG is the most common active material for these purposes because of its favorable optical and thermal characteristics and the availability of cheap, high-power pump diodes [1,2]. Although many different pumping schemes and laser types are available nowadays, diode-side pumped Nd:YAG rod lasers (DPSSL) are a very competitive technology because of their proven reliability, power scalability, simplicity, availability and low cost of components [3-5]. Nowadays, there exists a large variety of such modules available on the market. Average multi-mode output powers are in the range of tens to several hundreds of watt for these modules and they can be acquired with a series of stacked diode bars arranged in a two, three or fourfold symmetry around the laser rod.

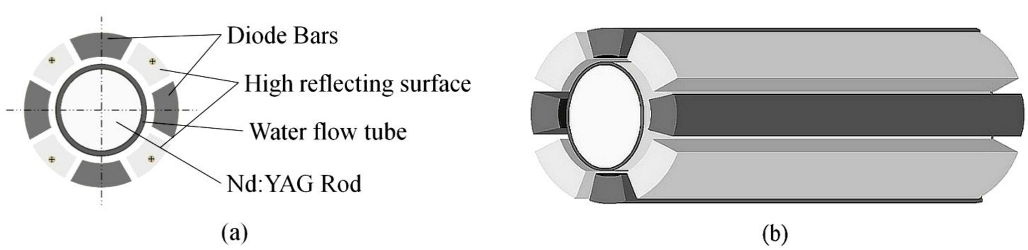

Figure 1: Scheme of a typical commercial DPSSL module. (a) Front view and (b) side view.

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Figure 1 shows the schematic view of a typical DPSSL module. Generally, the stacked diode bars do not receive any fast axis collimating lenses, because the proximity to the rod, its high index of refraction and curved surface already act in a lens like fashion. Additionally, a reflector is positioned on the side opposite to the diode stack to generate a second pass of the non-absorbed pump radiation through the crystal that acts, together with the low doping concentration of only 0.6 at.% neodymium, as an effective pump radiation homogenizer. Usually, stable TEM_{00} mode operation in rod-lasers is only achieved at a specific pump power due to limitations imposed by optical and mechanical distortions of the laser material induced by the heat load generated during high pump power operation. These distortions manifest themselves mainly as thermally induced lens and thermally induced birefringence (TIB) which causes, amongst other effects, bifocusing. To extract large output powers in fundamental mode operation, one would like the TEM_{00} spot size as large as possible inside the rod but not too large in order to avoid diffraction effects at the border of the rod. Therefore, to achieve high TEM_{00} output power with these modules, the optimization of two parameters is necessary: (i) the TEM_{00} mode-spot size inside the rod, w_{30}, and (ii) the pump power at which the TEM_{00} mode radius inside the rod reaches a minimum value. Generally, the mode spot size inside the rod of radius r is chosen such that r/w_{30} is of the order of 1.5 to 2.2 in order to prevent the oscillation of higher-order modes. It has been shown that every laser resonator containing a thermal lens has two stability zones [6]. Cerullo demonstrated that the stability zones can be joined, providing resonators with a wide dynamic range of operation, composed of both individual zones I and II [7].

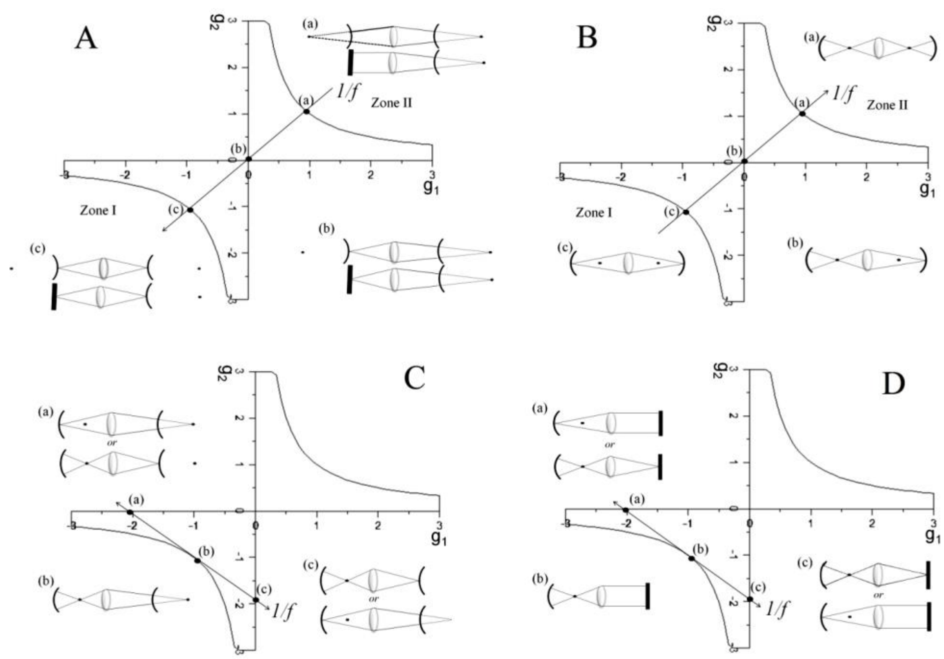

Figure 2: Positive Slope Resonators: A – with low misalignment sensitivity for high dioptric powers. B – with low misalignment sensitivity at low dioptric powers. Negative Slope Resonators: C and D – maximum misalignment sensitivity in the middle of the stability range, inverting the positions of input and output mirrors the arrow will present one of the directions indicated in the diagram: the upper graphs in (a) and (c) correspond to the downwards arrow.

This makes the use of joined stability zones resonators a good choice for working with laser cavities that are occupied by large fundamental TEM_{00} modes (w_{30}) inside the laser rods, which is necessary for high output powers [8-11]. Nevertheless, the maximum TEM_{00} spot size inside the rod cannot surpass 1.1 mm due to thermally induced birefringence, regardless of the size of the laser rod[12]. Therefore, given that r/w_{30} is ideally around 1.8 [6], maximum rod size is 4 mm in diameter. This limits the output power for TEM_{00} operation despite the fact that current crystal growth techniques allow obtaining large Nd:YAG rod diameters. Even 4 mm is already on the verge of what can be called "dynamically stable", once the stability interval is so short that the resonator will effectively work in TEM_{00} mode at only one operation point of pump powers. For any other pump powers one part of the laser beam will be either highly diffracted and/or unstable.

2. LASER SET-UP

We have demonstrated this concept in several solid-state lasers including in laser active materials such as $Nd:YVO_4$ and $Nd:YLF_4$ [13,14]. Using Nd:YAG rods, first a lamp-pumped laser was constructed and then the first diode pumped dynamically stable laser (DPDSL) using stacked diode bar modules was developed with a record 60% extraction efficiency when compared with multimode operation [15,2]. This first DPDSL laser used a quarter-wave plate and a flat output coupler in order to achieve efficiency with polarized operation. In a second step a 100 W standing-cavity, polarized DPDSL was developed using two modules and a half-wave plate in between them [16].

Upon polarizing the laser, two sets of thermally induced lenses are obtained, vertical and horizontal polarized lenses. Each set consists of a tangentially polarized lens and a radially polarized lens. As can be demonstrated, under homogeneous pumping conditions, the ratio between the focal length of both lenses, tangential and radial, is 1.2. However, for polarized lasers this ratio is only true for the average, unpolarized lens. If pumping conditions are inhomogeneous, as for example in a three-fold diode-stack pump-symmetry, the ratio can become 1.1 for one polarization and 1.3 for the other polarization. This has profound implications on beam quality and output power, as we have demonstrated recently and where we have achieved a beam quality of $M^2 = 1.02$ [17]. The latter work was a development for a pump laser for a mid-infrared OPO. Although the beam quality and output power of the pump laser were more than enough, it was missing spectral quality.

With this work we are focusing on the development of a single-frequency DPDSL. For this purpose we are using an unidirectional ring cavity as shown in the photo below.

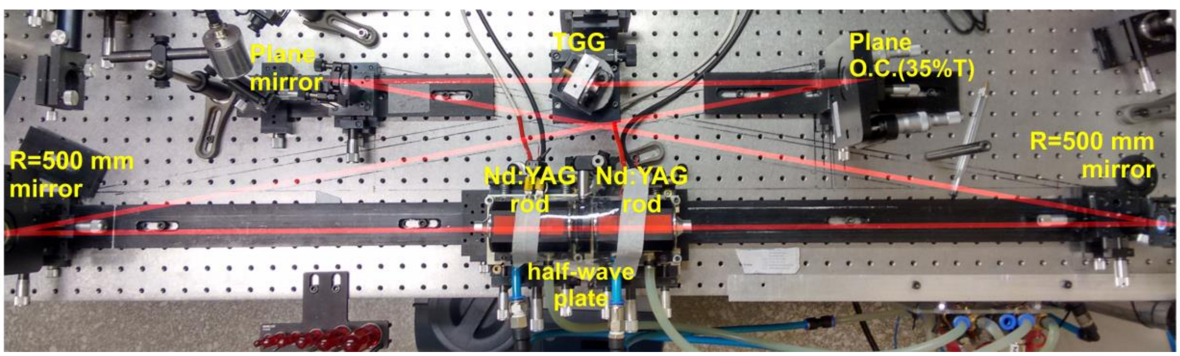

Figure 3: Set-up of the Ring-resonator composed of two Nd:YAG laser rods, a half-wave plate and a Faraday rotator, two curved and two plane mirrors, one of them with output coupling of 35%.

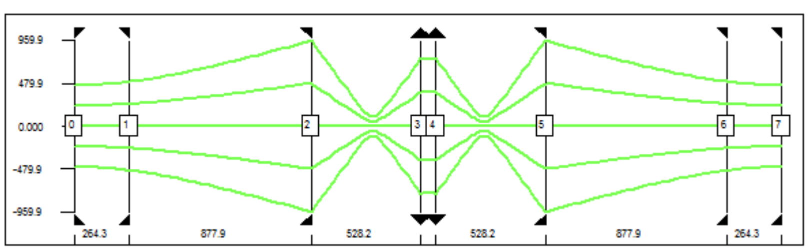

Figure 4: Mode plot of above resonator. Beam waist inside laser rods is approximately 750 μm.

The laser was composed of two laser rods (Nd;YAG 0.6 at.% doping) of 78 mm length, pumped each of them by 12 diode bars arranged in a three-fold symmetry around the rod with a total of up to 224 W of optical pump power. Two curved mirrors of radius +50cm and two plane mirrors closed the laser cavity. A Terbium gallium garnet (TGG) Faraday rotator was used to guarantee unidirectional operation in conjunction with the half-wave plate introduced between both rods. Total cavity length was approximately 348 cm. A mode plot of the resonator is shown in Figure 4.

3. RESULTS

3.1 Optimization of output coupling

We first optimized output coupling for the unpolarized laser (bidirectional operation), using output couplers that varied from 7% to 70% transmission, as shown in Figure 5.

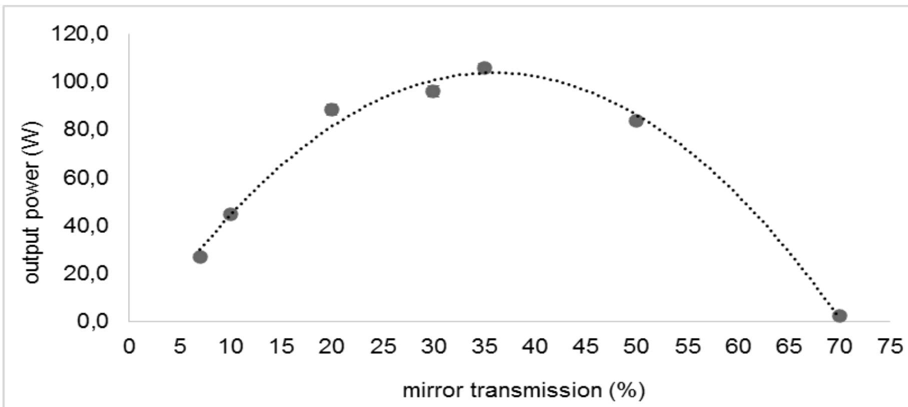

Figure 5. Continuous laser output power as a function of output coupler transmission. The laser was unpolarized and operated with a low M^2 beam.

Using a mirror with 35% output coupling, a maximum output power of 105 W was achieved., as shown in

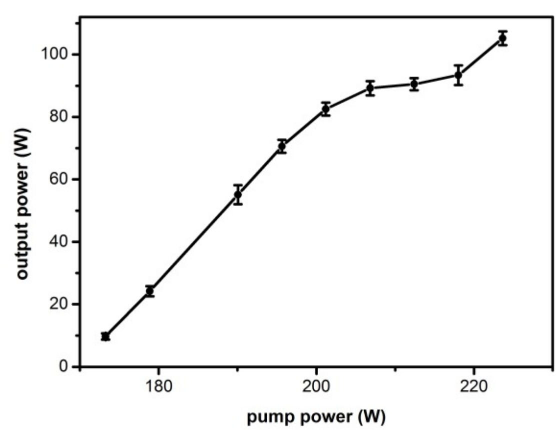

Figure 6. Output power as a function of pump power at 806 nm using the 35% transmission outcoupling mirror. The pump power is the calculated optical power per module; there are two modules in the resonator.

In Figure 6 we observe an almost linear output power increase over a wide range of pump powers, starting at 170 W and up to almost 230 W. During the whole dynamic range of operation the beam quality tends to remain between M^2 =1 and M^2 =2 [17]. This is one of the advantages in operating with resonators that use the mode-filling technique [6,7].

Maximum output power was 105 W of output power for an output mirror with 35% transmission. The beam quality was $M^2 = 1.71$ and $M^2 = 1.56$ in horizontal and vertical directions, respectively, as shown in Figure 7. The beam quality was measured directly behind the output coupler and improvements can be expected with measurements that are obtained more carefully once the center of the beam has a well-behaved shape.

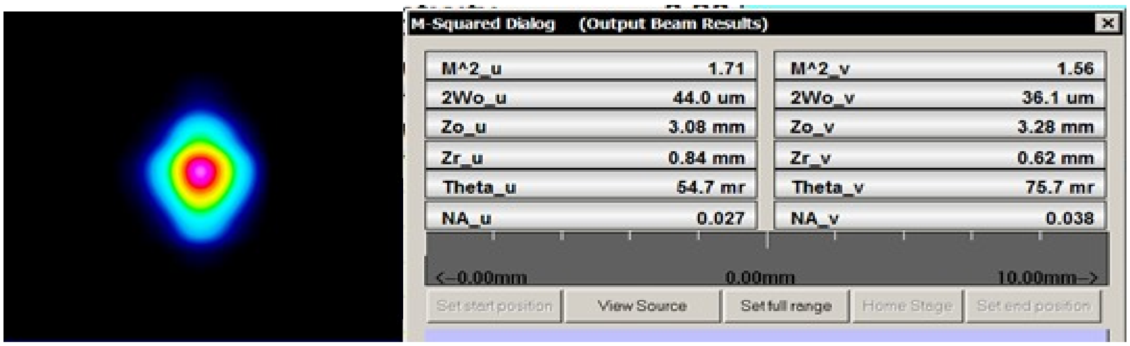

Figure 7: Photo of the beam and measured beam quality at maximum output power. The measurements were done with a Dataray Beamscope P8.

3.2 Single frequency operation

After achieving unidirectional operation of the laser using a Brewster cut TGG and a half-wave plate between the two laser rods, the laser show a very noisy output dominated by a residual frequency modulation of 13.5 GHz as shown in Figure 8.

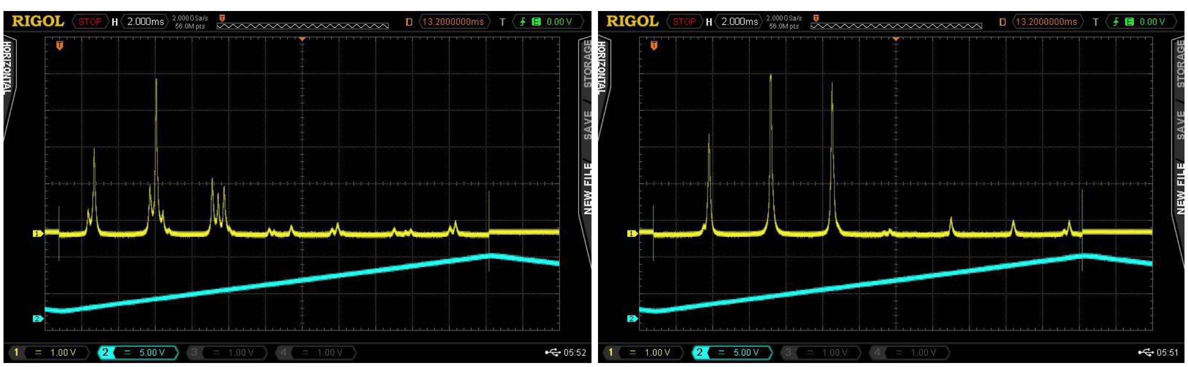

Figure 8: Different instances of the spectrally modulated unidirectional output (three sets of peaks to the left) measured using a Fabry-Perot of 2.85 MHz resolution.

In order to suppress the modulation and mode-hopping temporarily, we inserted an etalon into the cavity (uncoated fused quartz of 10 mm thickness) which was capable of stabilizing one single frequency within the cavity for several seconds (5-10 s). The final output power in this configuration was above 40 W. The single frequency shown in Figure 9 has a FWHM of approximately 10 MHz.

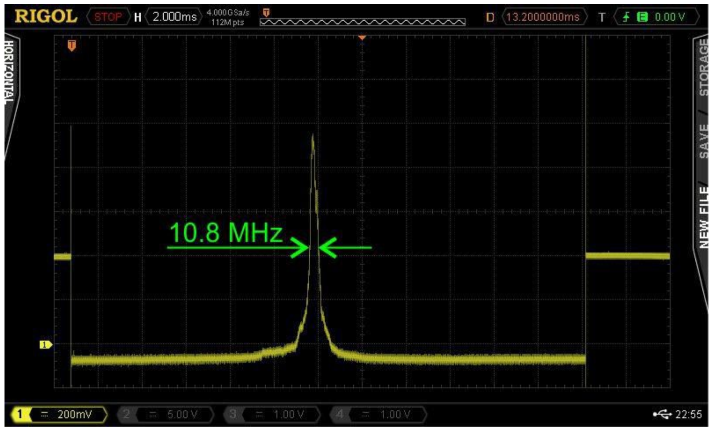

Figure 9: Single frequency output measured using a Fabry-Perot of 2.85 MHz resolution.

4. CONCLUSION

We have demonstrated a CW polarized ring resonator with near-TEM_{00} beam quality and output power of 105 W. The output power achieved is, to our knowledge, the highest reported for continuous polarized, fundamental-mode ring lasers using standard side-pumped Nd:YAG modules. In single-frequency operation, a maximum preliminary output power of 40 W and a linewidth of 10.8 MHz were achieved. Future work will include increase of beam quality and output power and an active stabilization scheme.

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