High power fundamental mode Nd:YAG laser with efficient birefringence compensation

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Abstract: Experiments on a high-power end-pumped Nd:YAG rod laser with an efficient birefringence compensation will be presented. A linearly polarized output power of 114 W with an M^2-value of 1.05 was realized. Furthermore, the from our best knowledge highest injection-locked single-frequency output power of 87 W in a nearly diffraction-limited beam was demonstrated.

OCIS codes: (140.3520) Lasers, injection-locked (140.3570) Lasers, single-mode (140.3580) Lasers, solid-state

References and links

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1. Introduction

For the next generation of gravitational wave detectors, based on large Michelson interferometers, high circulating laser power will be needed to increase the detector sensitivity. Therefore, interferometer arms with additional high finesse Fabry-Perot cavities will be used, to build up the injected laser power into levels close to one megawatt. This requires a laser source with nearly 200 W of output power in the fundamental mode and a stable single-frequency operation [1,2]. We present a design and the first results of a laser system suitable for the next generation of gravitational wave detectors.

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In presence of the thermo-optical effects in high power lasers it is a challenge to combine high power with excellent beam quality. In all different Nd:YAG laser concepts like rod, slab or disk lasers thermal gradients within the laser material cause thermally induced refractive index changes which lead to thermal lensing, aberrations and birefringence. For a gravitational wave interferometer a stable linearly polarized, fundamental mode laser source is required. Therefore, the depolarization as a result of the thermally induced birefringence becomes the limiting effect on power scaling. Especially in rod lasers Knoke and Murdough *et al.* [3,4] demonstrated that the linearly polarized output power of a single rod system is limited to a maximum of 45 W due to depolarization. To overcome this limit and to scale a rod laser design into the high power range, a double rod concept combined with a 90 degree quartz rotator is used to compensate the thermally induced birefringence [5,6]. Here the cylindrical symmetry of rods turns into an advantage compared to other laser designs as it allows an efficient compensation of the birefringence and the bifocusing, as shown below. Other advantages are the approved robustness and reliability of rod lasers as shown with high power lasers for material processing.

In order to achieve an output power of nearly 200 W in a diffraction-limited, single-frequency beam a ring laser with four identically diode- and end-pumped laser heads is planned. Each two of the four laser heads will be combined with birefringence compensation. To proof the concept the first experiments were performed only with two laser heads to optimize the birefringence compensation and the resonator design for fundamental mode operation. These prior investigations are recommended because of the symmetry of the final four-head ring laser. To achieve a stable single frequency operation an injection locking technique [7] was applied to transfer the stable frequency operation of a master laser [8] and an intermediate 12 W ring oscillator [9] to the high power slave laser.

2. Laser head design

To develop a laser source for gravitational wave detection important aspects like amplitude and frequency stability, reliability and long-term stability have to be taken into account in addition to laser output power and beam quality. Therefore, the following chapter will specify the different parts of the laser head.

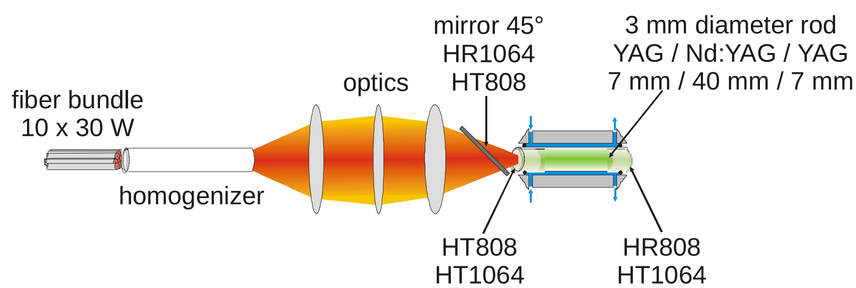

Fig. 1. End-pumped laser design with pump light homogenizer and double pass of pump light absorption.

2.1 Laser crystal

In order to achieve an excellent beam quality at high output power an end-pumped, low-doped, composite Nd:YAG laser rod was chosen, see Fig. 1. Maximum temperature and surface stresses at the rod ends are greatly reduced by diffusion-bonding of 7 mm long undoped regions to both ends of the 40mm doped rod [10,11]. With a low dopant concentration of 0.1 at.% and a double pass of the pump a light smoothed longitudinal temperature distribution is achieved within this configuration. The double pass of the pump light was realized by using total internal reflection at the rod surface and a highly reflective coating at one of the end facets. In Fig.2 the calculated temperature distribution on the rod-axis from a double pass 0.1 at.% doped and a single-pass 0.2 at.% doped crystal is compared (analytical solution [12]).

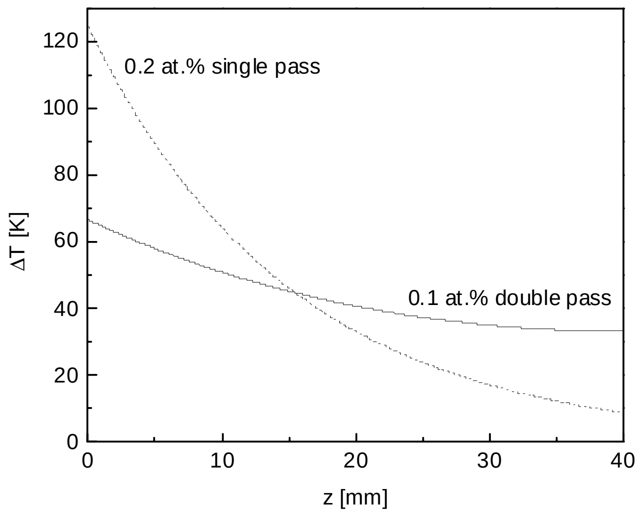

Fig. 2. Calculated temperature distribution on the rod-axis and the length of the doped region. Compared is a 0.1 at.% double pass with a 0.2 at.% single pass configuration.

It can be seen that the temperature difference along the rod-axis is 24 K for the 0.1 at.% and 117 K for the 0.2 at.% doped rod. These analytical results are in good agreement with our finite element analysis that was used to calculate the thermal lens and the thermally induced stress in the rod.

Temperature gradients inside the rod induce stress and thermo-optical effects and also affect the gain because of the temperature dependent emission wavelength of Nd:YAG. To investigate this temperature/gain dependence for high power longitudinally pumped rods, the temperature dependent fluorescence of Nd:YAG was measured. To achieve an almost uniform temperature distribution over the rod length the measurements were performed at low pump power and the temperature was tuned by the cooling water around the rod. The measurement shows a linear dependence between the temperature and the peak fluorescence with a thermal tuning coefficient of 0.0035 nm/K. Due to this temperature dependence, the gain over the rod length changes in high power longitudinally pumped laser designs. Especially for single frequency lasers the spectral overlap between the master laser frequency and the slave laser Nd:YAG line has to be optimized. For maximum gain extraction, the center of the 4.5 Å (FWHM) broad Nd:YAG line at 1064 nm (air) has to be used. To calculate the optimum overlap, the product of the Nd:YAG line profile *gain(λ,T)* and the laser line profile *laser(λ)* has to be integrated. Fig. 3(a) shows the convolution integral of the relative gain depending on the crystal temperature difference calculated for different laser line widths. It can be seen that the gain is reduced for high temperature difference and also that for smaller laser line width the gain is more and more reduced down to a line width of nearly 0.0045 Å. The Fig. shows that the gain curve for 0.045 Å and 0.0045 Å nearly overlap. For these narrow line widths, the gain follows the Lorentz gain profile of the medium because of the several times broader spectrum and therefore, the gain does not change any more with smaller laser line width. To calculate if a reduced gain has to be expected for the developed laser design the temperature dependent gain for single frequency laser operation was calculated with the temperature profiles shown in Fig. 2.

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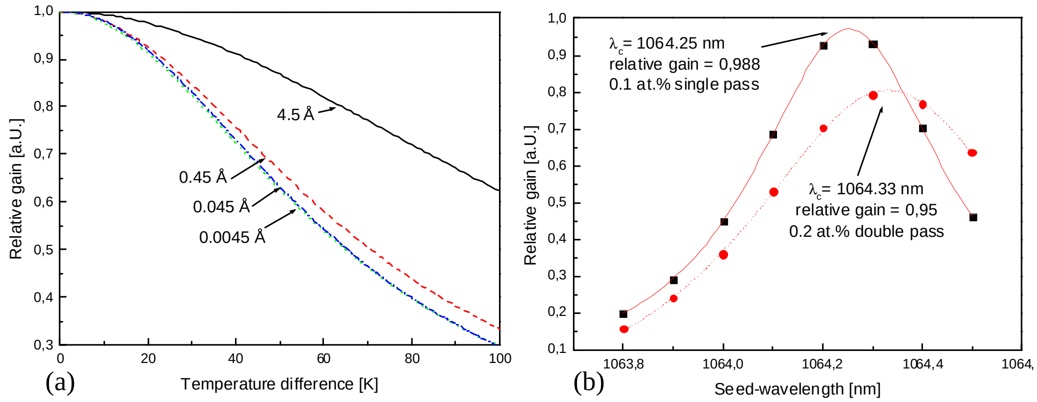

Fig. 3 (a) Relative gain for different seed laser line widths as a function of the temperature difference along the rod axis; (b). Relative gain integrated over the propagation length on a single frequency seed laser wavelength, calculated with the above described temperature profile for single and double pass configuration.

These values are multiplied by the absorbed pump power and integrated over the propagation length to calculate the extractable gain. Figure 3(b) shows this normalized gain depending on the seed laser wavelength. It can bee seen that with an optimized master laser wavelength 99 % and 95% of the maximum gain can be theoretically extracted with the double and the single pass configuration, respectively. In case of injection locking it is possible to tune the laser wavelength of the master laser, and therefore, the maximum gain of 99% should be extractable with the 0.1 at.% doped double pass rod design. These results showed that for temperature differences in the laser medium below 100 K the loss depending on the temperature dependent gain of Nd:YAG is below 5%.

2.2 Pump - diodes

Each laser rod was pumped with ten fiber-coupled laser diodes (fiber-core diameter 600 µm, NA 0.22, type JOLD-30-CPXF-1L), each able to deliver up to 30 W pump power but being operated with derated current (25 % below nominal value) to increase the lifetime of the laser diodes. Fiber-coupled diodes are chosen to allow easy maintenance and to keep the cooling water and the high operation current for the diodes apart from the laser head. Another aspect is the emission line width of the diodes which is narrower (typ. < 2 nm FWHM) compared to a diode-stack where the individual bars show slightly different center wavelengths, which leads to a broader emission spectrum (typ. 4 nm FWHM) as they are cooled to the same temperature. For the temperature control of each diode a computer-based PID controller with an accuracy of 0.03K was used. Therefore, a spectral overlap of the ten diodes with an overall emission spectrum of < 2.5 nm FWHM was achieved. These results in a good spectral overlap with the absorption spectrum of Nd:YAG and an effective absorption coefficient of 0.359 cm^{-1} at 808 nm. With this setup the temperature stability of the diodes accomplished an almost constant absorption over the laser crystal which is not feasible with water-cooled laser diodes because of the lower temperature stability.

2.3 Pump light homogenization

In order to avoid that every individual fiber output can be observed in the spatial pump light distribution and results in beam distortion, a pump light homogenization was used. This was accomplished by using a 3 mm diameter fused-silica rod which was connected to the fiber ends. The pump light was mixed and guided by total internal reflection inside the rod.

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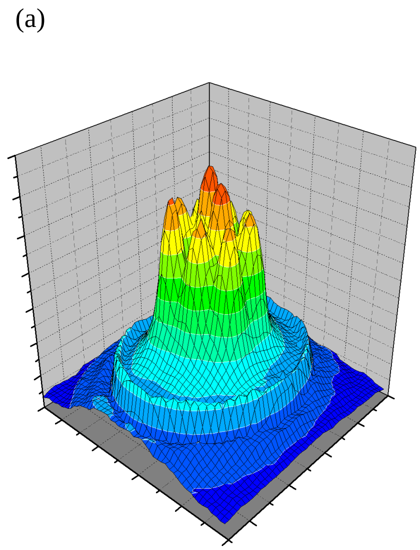

Fig. 4. Measurements of the fluorescence (integrated over the rod axis) without (a) and with (b) pump light homogenization.

Figure 4 shows the fluorescence-distribution without (a) and with (b) the homogenizer. It can be seen that with the pump light homogenizer a more uniform and smooth distribution was achieved.

A second advantage of the homogenizer is a kind of “soft failure handling” since it is possible to compensate diode laser degradation or diode failure. This can be accomplished by increasing the output power of the residual operating pump diodes to keep the pump power fixed, while the spatial pump light distribution remains almost unchanged. Therefore, the concept allows an on-line maintenance or diode laser exchange also during laser operation, which is an essential feature to avoid laser downtimes e.g. in gravitational wave detectors.

The laser performance *with* as well as *without* the homogenizer was investigated in a standing-wave resonator. The experiments have shown that using the homogenization, the laser output power can be increased by almost 30%. The results can be explained with the change of the thermal lens in case of the modified and smoothed pump-light distribution. As a rule of thumb, less aberrations and a better gain overlap let increase the output power. The dependence on laser output power with different pump-light distributions where further investigated in Reference 13.

2.4 Pump spot size

In case of the low brightness pump source resulting from the fiber bundling and of the needed space for the 45° mirror, a three lens telescope has to be used to launch the pump power into the laser rod. In order to optimize the pump spot size, single pass gain measurements were performed. As seed source an NPRO (non planar ring oscillator) was used. A spot size of 600 µm in radius in the laser rod was chosen as this size was close to the expected fundamental mode size of the laser design. With a pump spot size of 0.9 mm in radius the highest single pass gain of 3.2 at a launched pump power of 215 W was achieved. Due to the smaller pump spot the single pass gain was 28 % higher compared to a spot size of 1.3 mm. The results were also verified experimentally in a standing wave resonator (Fig. 5) where an 18 % output power increase was achieved. The results were in a good agreement to the measurements of reference 14 where the optimum pump to mode size ratio was investigated. The results show that the pump to mode size ratio should be arranged to a value lower than 1.6 which is given for the 0.9 mm pump spot size.

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3. High power oscillator

3.1 Birefringence compensation

Transversal thermal gradients in laser rods are causing refractive index changes in radial and tangential polarization directions (birefringence) and therefore lead to depolarization and bifocusing. The birefringence can be compensated with a 90° quartz rotator in-between of two identically pumped rods, see Fig. 5 and references [5,6]. With this combination the thermally induced optical path length differences caused by the first laser rod can be compensated in the second one and vice versa only by interchanging the radial and tangential polarizations. To achieve the most efficient birefringence compensation the planes of maximum thermal gradient are imaged onto each other. The employed relay-optic promised, according to our calculations, the best compensation compared to a single lens and a non-imaging setup. The calculations predict depolarization of 0.1%, 0.3 % and 2.1 % for relay-optic, single lens and non-imaging, respectively.

The efficiency of the birefringence compensation was verified experimentally in a standing wave resonator, see Fig. 5. The setup consisted of two identical laser heads with the pump setup described above. A plane 45° mirror being highly reflective for 1064 nm and highly transmittive for 808 nm was used to separate the laser radiation and the pump light. Two identical convex lenses (f = 100 mm) constituted the relay-optic for the birefringence compensation provided by the 90° quartz rotator (QR). The resonator was completed by a highly reflective end mirror on one end and a 20% output coupler on the other end. The Brewster plate (BP) accomplished linearly polarized radiation.

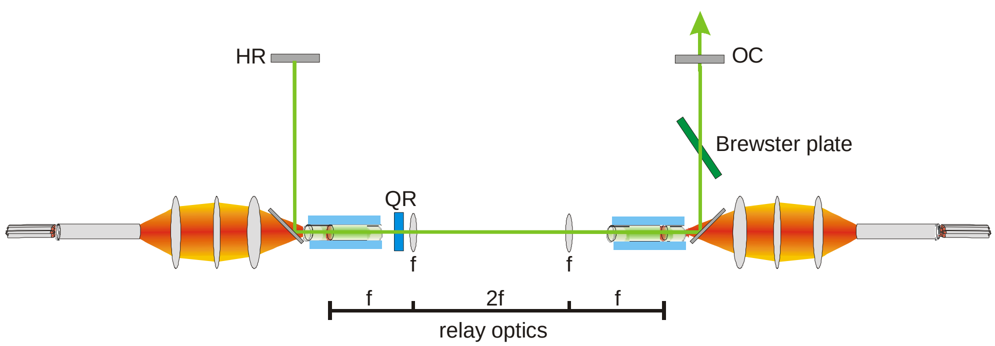

Fig. 5. Setup of the standing wave resonator with birefringence compensation. OC: output coupler, HR: highly reflective mirror, QR: quartz rotator.

The first experiments were performed in non-polarized operation without a BP and without a QR and a maximum output power of 94 W was achieved (Fig. 6(a)). The laser output power dropped down at a launched pump power of nearly 380 W. Here the bifocusing acted and the resonator became unstable for the radial polarization direction. In Fig. 6(b) the resonator stability for the two polarization directions and for the compensated resonator are shown. It can be seen that the resonator became unstable for the radial polarization at nearly 380 W which reduced the laser output power. The laser output power of the unpolarized operation with QR in place showed that the pump power can be further increased because of a stable resonator for both polarization directions. The output power decrease at 128 W with a launched pump power of nearly 400 W. At this point the compensated resonator became unstable. The results showed that the bifocusing can be efficiently compensated with this

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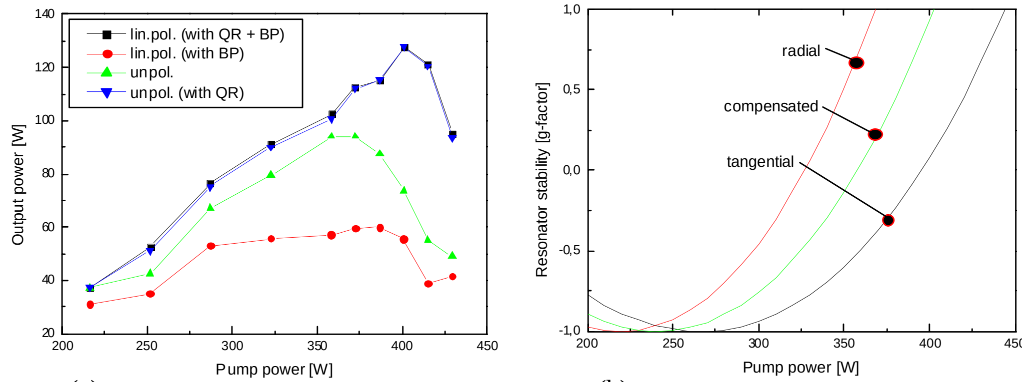

(a) (b)

Fig. 6 (a) Comparison of the laser output power characteristics with and without birefringence compensation in polarized and non-polarized operation; (b). Laser stability diagram for radial, tangential polarizations and for the birefringence compensated resonator.

setup. Depolarization losses only occurred in linearly polarized operation. A BP was placed inside the resonator and the QR was taken out of the resonator. The Fig. 6(a) showed that the laser output power is limited below 60 W due to depolarization. With the QR in place the linearly polarized output power can be increased and the same output power as in non-polarized operation was obtained. The results show that an efficient birefringence compensation of 100% was obtained if maximum output powers in non-polarized and polarized output power are compared.

3.2 Fundamental mode operation

For a gravitational wave interferometer a Gaussian laser beam is needed to allow an efficient coupling of the laser power into the high-finesse Fabry-Perot cavities of the interferometer. Therefore, the resonator shown in Fig. 5 was optimized for a stable fundamental mode operation. With a pump power of 200 W per rod a stable, linearly polarized TEM_{00} output power of 114 W was achieved. Measurements of the laser beat-signals with a fast photo-diode and an electrical spectrum-analyzer verified fundamental mode operation of the system as no higher order modes can be detected. The beam propagation factor M^2 was measured to be below 1.1.

3.3 Injection locking

In order to achieve a stable single-frequency operation injection locking was applied to transfer the frequency properties of a master laser (Master), based on a non-planar ring oscillator [8] (NPRO, *Mephisto 2000*; Innolight) via an intermediate 12 W ring oscillator (Slave I) [9] to the high-power slave laser (Slave II). An active length control system based on the Pound-Drever-Hall scheme [7] was used to keep the difference between master and slave laser cavity frequencies to a value within the injection locking range. A first electronic system stabilized the 12 W laser cavity to the frequency of the NPRO. The second one forced the high power slave cavity to the frequency of the 12 W laser. These first two stages are similar to the one used for the GEO 600 laser [9] which is operating up to now for more than two years in a stable operation. To lock the high power laser, the double-head laser design of Fig. 5 was used in a ring resonator configuration, see Fig. 7. The free running slave laser operates at an output power of 81 W. With this setup a stable linearly polarized, single-frequency and nearly diffraction-limited beam with 87 W output power, an optical-to-optical efficiency of 23 % and an M^2 = 1.1 was demonstrated. This is, to the best of our knowledge, the highest injection-locked output power of a solid state laser system.

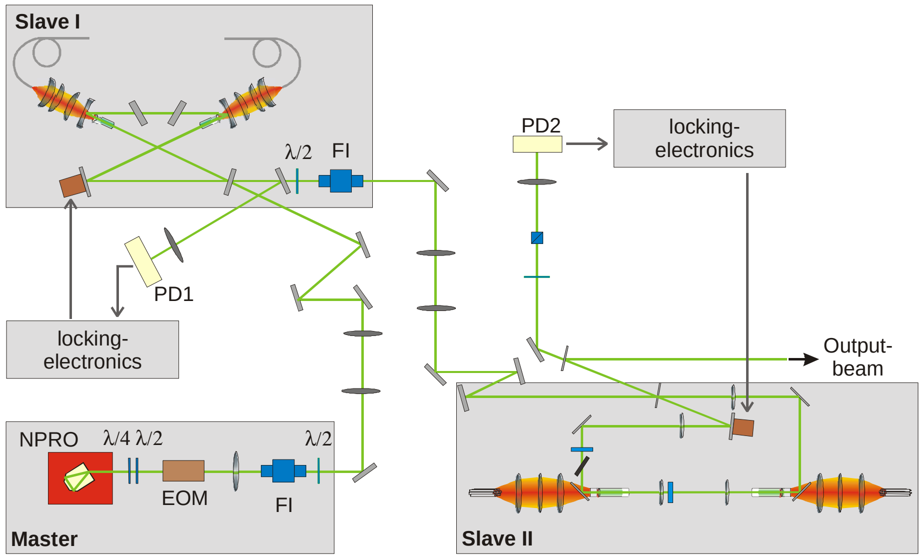

Fig. 7. Injection locking setup of the triple stage design. FI: Faraday Isolator, EOM: Electro-Optical Modulator, NPRO: Non-Planar-Ring Oscillator, PD: Photodiode, λ/2: half wave plate/2, λ/4:quater wave plate/4

These experiments were performed with non-optimized laser heads, i.e. without pump-light homogenization and without optimized pump spot size. Therefore, less output power compared to the presented standing wave resonator experiments where obtained. But the experiments showed that the complete output power of the free running ring laser can be transferred to single frequency operation.

Fast and stable locking electronics enable a stable single-frequency operation. For some accidental interruption of injection locking operation e.g. by strong mechanical shock to the optical table an auto-lock feature was implemented. The auto-lock applied a saw tooth voltage to the piezos which change the cavity length. If the frequency of the master and the first slave (Slave I) laser coincide, the slave laser operates in an unidirectional instead of a bidirectional mode, so that the photodiode PD1 detects a two-times higher laser output. The resultant increase of the photodiode output current triggers the servo for the Pound-Drever-Hall stabilization which locks the cavity length of slave I to the master. If the first two systems (Master and Slave I) are locked, the second locking to the high power laser (Slave II) was started with the same procedure between slave I and slave II using PD2 and additional locking electronics. Typically the “re-lock” time of the complete system took less than 400 ms.

4. Summary and outlook

We presented a high power Nd:YAG rod laser design as a potential laser source for advanced gravitational wave detectors. An efficient birefringence compensation was demonstrated and the same output power for polarized and un-polarized operation was obtained. It was shown that rod lasers can be scaled above the 100 W level with excellent beam quality. We achieved 114 W in a fundamental mode and diffraction-limited beam. Furthermore, a stable single frequency operation with 87 W of output power was demonstrated. These results show that it is possible to scale rod lasers to high output power in a fundamental transversal mode.

In order to scale the presented design to the 200 W level four instead of two laser rods will be used in a ring resonator configuration. For a stable linear polarization each two of the four laser rods are planned to be combined with a birefringence compensation similar to the design shown in Fig. 5. The advantage of this scaling concept is that the thermal effects in the laser rods are well known and compensated and not expected to change with the modification using four instead of only two laser heads. Hence, this scaling concept and our first experiments let us expect a single frequency output power close to the 200 W level.

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