Fundamental mode, single-frequency laser amplifier for gravitational wave detectors

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Abstract: An amplifier design for efficient amplification of linearly polarized fundamental mode lasers is presented. The concept was verified by amplifying single-frequency input powers from 1 W to 20 W into output power ranges of 35 W up to 65 W. Beam quality measurements with a mode-analyzer cavity showed only minor beam quality degradation due to the amplification process.

OCIS codes: (140.4480) Optical amplifiers; (140.3580) Lasers, solid-state

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1. Introduction

High power, low noise, fundamental spatial mode, single-frequency lasers are required for laser interferometric search of gravitational waves [1-3]. The standard single-frequency master laser is a Non-Planar-Ring-Oscillator (NPRO) with a maximum output power of 2 W [4]. For the initial gravitational wave interferometers this master laser power was increased by injection-locking or amplification to reach power levels of 10-20 W [5-7]. All initial

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gravitational wave detectors are limited by shot noise at higher signal frequencies and for higher sensitivities a laser power increase is required. First incremental upgrades are planned for the gravitational wave detectors currently in operation which require laser power in the 50 W range. In a second step like in the advanced LIGO project larger changes are planned which include upgrades of the power-handling capability of the interferometers to allow for laser input power levels of several hundred watts. Therefore, a 200 W laser source is already under development [8].

We present an amplifier design for the application of gravitational wave detection which can be applied to upgrade the currently used laser systems to an output power of 65 W (with 20 W seed) or to amplify an NPRO to 35 W of output power. Detailed investigations of the laser spatial beam-quality and relative intensity noise as well as beam-pointing fluctuation have been carried out to investigate the suitability of the presented laser design for gravitational wave detection.

2. Laser design

An end-pumped laser design was chosen to achieve a well defined mode control and an efficient amplification with excellent beam quality. The chosen laser material Nd:YVO_4 is a high gain material which is naturally birefringent such that only low depolarisation effects occur. On the other hand the material properties of Nd:YVO_4 like thermal conductivity and mechanical hardness limit the Nd:YVO_4 application to the medium power range. In the presented amplifier design, each laser crystal was pumped by a 400 µm diameter, NA: 0.22 fibre-coupled laser diodes delivering a maximum output power of 45 W. The laser crystal (3 mm x 3 mm cross-section and 10 mm long) consist of a 2 mm undoped and a 8 mm 0.3 at.% doped region. The undoped region was used to reduce the maximum temperature at the pump entrance side [9]. To separate the pump light from the laser light, a dichroic 45° mirror with anti-reflection coating for the pump wavelength and high-reflection coating for the laser wavelength was implemented. Efficient cooling of the laser crystal was realized by mounting the crystal wrapped into a 500 µm thick indium foil in a water-cooled copper block. Figure 1 shows a schematic setup of the four stage amplifier design with an NPRO seed source.

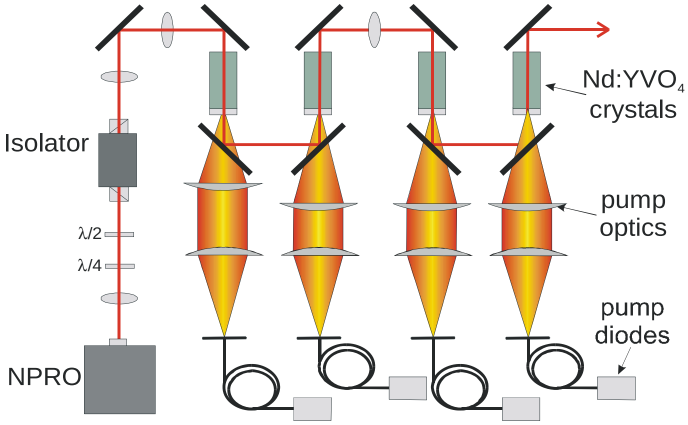

Fig. 1. Setup of the four stage amplifier design with an NPRO seed source.

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3. Experimental results

3.1 Output power

To achieve an efficient amplification of a Nd:YAG single-frequency laser source with a Nd:YVO$_4$ amplifier the laser emission wavelength of the Nd:YAG NPRO has to be adapted because of the slight different peak emission wavelengths of the two laser materials. The wavelength matching can be done by temperature tuning of the NPRO. Figure 2 shows the temperature dependency of the peak emission wavelength for a Nd:YAG NPRO and the used Nd:YVO$_4$ laser crystal. The temperature dependency of the Nd:YVO$_4$ crystal was investigated by measuring the fluorescence peak at low pump power and tuning the water temperature of the crystal mount. It was verified experimentally that in the shown temperature range the maximum gain was achieved. This is due to the fact that the emission wavelength of Nd:YVO$_4$ is quite broad with 0.9 nm (FWHM) and the line width of the NPRO is in the range of a few kHz [10]. The dashed line of Fig. 2 shows the calculated range in which the gain is reduced by less than one percent. Therefore, the NPRO can be operated in its standard temperature range (25-40°C) to achieve efficient amplification with the presented Nd:YVO$_4$ amplifier design.

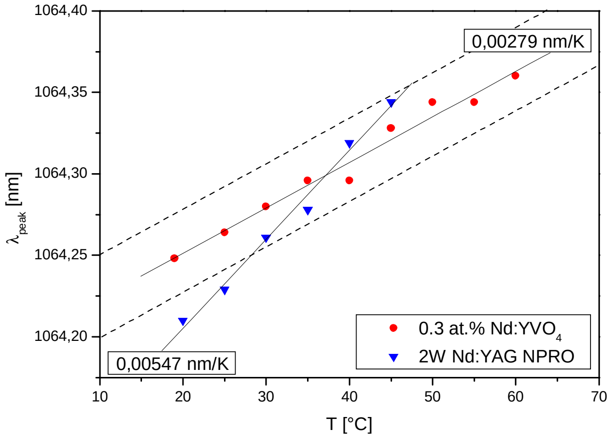

Fig. 2. Temperature dependency of the laser emission of Nd:YAG and Nd:YVO$_4$.

In order to realize an efficient amplification for small seed-laser input powers (< 2 W) the first amplifier stage has to be optimized to achieve early gain saturation. Therefore, two appropriate pump spot diameters (600 µm and 800 µm) with corresponding seed laser diameters of 400 µm and 600 µm were investigated. The 600 µm pump spot diameter was verified experimentally as the smallest usable diameter as at full pump power of 45 W beam quality degradations occurs. Figure 3 (left) shows the output power and the amplification factor versus input power for the first amplifier stage. The increase of output power for low input powers and the smaller pump spot size is due to the fact that the amplifier is higher saturated since the extracted output power of an amplifier is heavily depending on the gain saturation [11]. At a pump spot size of 800 µm the seed laser size was approximately 600 µm and therefore the calculated saturation power is about 3.4 W. For the smaller pump spot size of 600 µm the seed laser was 400 µm and the saturation power is about 1.5 W. The measurement proved that if the signal power is closer to the saturation power more output power can be extracted. For higher seed laser powers the two different gain curves approaches each other. For the first amplifier stage and the 600 µm pump spot size an output power of 6.6 W was achieved. This output power was higher than the saturation power of the 800 µm

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pump spot and therefore all further stages were pumped with the larger spot size of 800 µm. The increase of the pump spot in the additional amplifier stages was mainly to prevent beam distortions as the thermal optical effects strongly depend on the pump spot size [12]. With a pump power of 38 W per stage and 1.6 W of input power output power levels of 13.6 W, 22 W and 33 W after the second, third and fourth amplifier stage were achieved. The optical-to-optical efficiency of the fourth amplifier stage increases due to the stronger saturation up to 29 %. Figure 3 (right) shows the output power versus input power for one up to four amplifier stages in series.

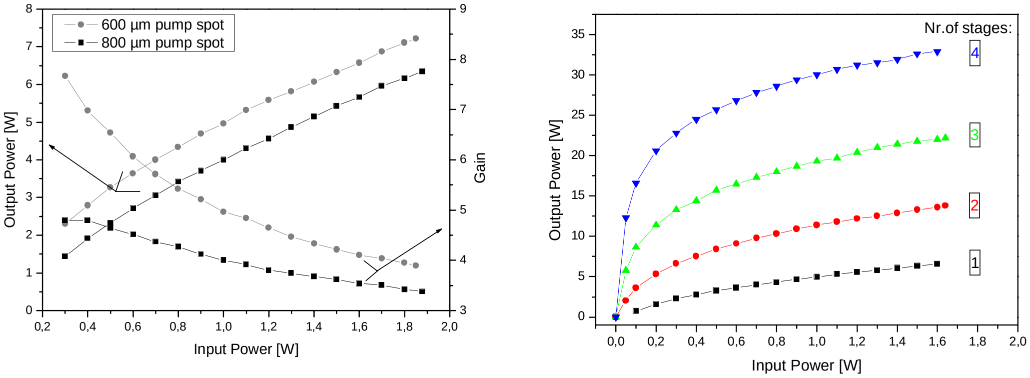

Fig. 3. (left) Output power and amplification factor versus input power for a single amplifier module pumped with 38W of pump power. (right) Output power versus input power for 1 up to 4 amplifier stages in series.

3.2 Beam quality

By the use of a 2 W NPRO (Mephisto 2000, Innolight) as the seed laser source an output power of 15 W and 36 W was achieved after the second and fourth amplifier stage, respectively. A crucial requirement for lasers used in gravitational wave interferometers is the spatial beam profile. The important quantity is the fractional power of the laser beam in the fundamental Gaussian mode TEM_{00}. To measure this quantity a mode-analyzer cavity was used [13, 14]. The cavity consists of a three mirror ring cavity with a finesse of about 200 where one of the mirrors is mounted on a piezo-electric element to enable a length scan of the cavity by more than a free spectral range (FSR). This scan allows a complete analysis of the mode content of the injected laser beam. Figure 4 shows a mode scan of the amplified NPRO beam after the fourth amplifier stage at an output power of 36 W. In the normalized curve, only the two fundamental mode peaks spaced by one FSR of the cavity and two tiny higher order modes can be seen (solid line). In the magnified view (x 100) some higher order mode peaks can be seen (dotted line). To analyse the power within the $TEM_{0,0}$ mode the ratio between the fundamental mode and the sum of all higher order modes was calculated. The results show that almost 95 % of the power was in the $TEM_{0,0}$ mode. The same measurement was performed on a two stage amplifier with an output power of 15 W where 97 % of the power was in the $TEM_{0,0}$ mode. For comparison, the $TEM_{0,0}$ mode content of the 2 W NPRO was as well determined to be 97 %. The results show that no significant beam distortion was added by the first two amplifiers. The four stage amplified beam has a slightly higher fraction of its power in higher order modes but still meet the spatial purity requirement for gravitational wave detectors which is generally set to less than 10 % of the beam power in higher order modes.

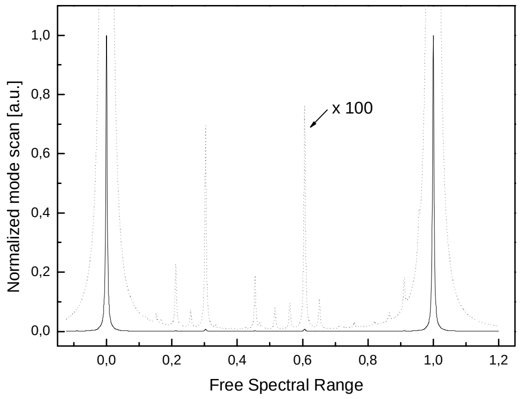

Fig. 4. Mode-analyser scan to verify the content of the TEM0,0 mode compared to other higher order modes. In the magnified scan some higher order modes can be distinguished.

3.3 Relative power noise

Further important laser characteristic for the use in the field of gravitational wave research is the additional intensity noise added due to the amplification process. Therefore a relative intensity noise (RIN) measurement for the NPRO, the two amplifier designs (2 and 4- stage) and the pump power were performed. Figure 5 shows the measurement in the gravitational wave detection relevant frequency range of 10 Hz to 10 kHz. The data show that compared to the NPRO the RIN was slightly reduced by the amplification at frequencies below 50 Hz. The effect can be explained by the saturation level of the amplifier which “filters” the noise at low frequencies. At frequencies above 50 Hz up to a few kHz the pump power noise determines the noise of the amplifiers. At higher frequencies the pump noise influence decreases and the amplifier noise approaches as expected to the NPRO noise. In conclusion, we have measured that in the range of 50 Hz up to a few kHz the noise of the pump diodes dominates the RIN while in other frequency ranges the NPRO noise determines the noise level.

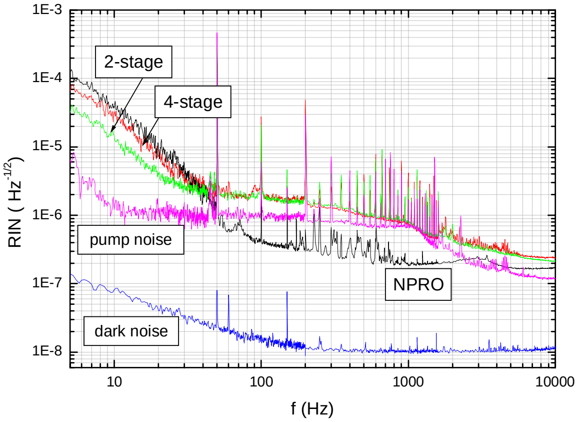

Fig. 5. Measurement of the relative intensity noise for the two and four stage amplifier design.

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3.4 Beam pointing

Beside the common known laser beam properties like power, beam quality and intensity noise also the beam pointing stability is an important parameter for the application of gravitational wave detection [15]. As the laser beam is coupled into a suspended mode-cleaner each pointing of the laser beam will couple into additional noise and higher order modes. Therefore, the pointing of the developed laser systems was measured with the diagnostic bread board presented in Ref. [14]. The value of the pointing is expressed in epsilon which has the following relation:

$$\varepsilon = \left[\left(\frac{\delta\alpha(f)}{\theta_D} \right)^2 + \left(\frac{\delta x(f)}{\omega_0} \right)^2 \right]^{1/2}$$

with $\delta\alpha$ and θ_D being the angle fluctuations and the divergence angle of the beam, respectively, and with δx and ω_0 being the translational fluctuations and the waist size of the beam, respectively. With this formula the pointing fluctuations can be calculated at each point of the beam defined by the beam waist size and the divergence angle. Our measurement of the pointing showed that the pointing decreases by one over the frequency with a value of $\varepsilon = 2.5 * 10^{-4}$ [$\mathrm{Hz}^{-1/2}$] at a frequency of 10 Hz. This value is for example close to the specifications of the advanced LIGO laser.

3.5 Further power scaling

Beside the presented amplifier results with an NPRO seed source the use of the amplifier as an upgrade for higher power laser systems was investigated. Figure 6 shows the output power of the four stage amplifier versus input power variation from 1 W up to 18 W. With a seed laser power of 10 W or even 18 W the output power can be scaled to power levels of 52 W or 64 W, respectively. Therefore, the overall optical-to-optical efficiency was 24 % and 33%. The beam quality factor M^2 was always less than 1.1. As the beam quality was comparable to the measured values for the NPRO seeded experiments we expect also comparable mode content in the $TEM_{0,0}$ mode.

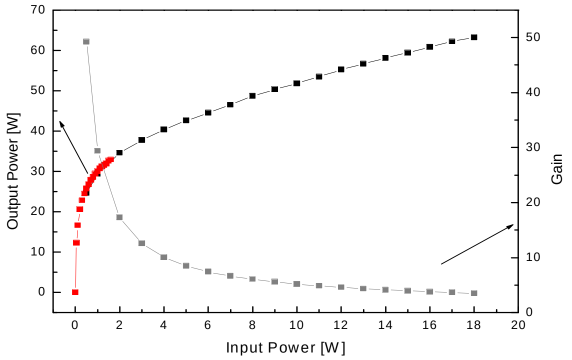

Fig. 6. Output power versus input power for the four stage amplifier and seed laser powers up to 18 W.

If the amplifier was not optimized to the spatial mode quality, which means pumped with maximum pump power of 45 W per stage and therefore a slight decrease in beam quality ($M^2 < 1.3$) even 80 W of output power could be realized with 18 W input power.

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4. Summary

It was demonstrated that efficient amplification of a Nd:YAG single-frequency, fundamental mode laser with Nd:YVO_4 as amplifier material is feasible. With a 2 W NPRO as seed laser source output power levels of more than 35 W were achieved. If the amplifier was seeded with higher power levels, for example with one of the currently used gravitational wave laser systems (10 W to 20 W) output power levels up to 65 W could be realized. The beam quality factor M^2 of all the experiments was measured to be less than 1.1. Measurements with a mode-analyser cavity verified the beam quality and shows that almost 95% of the amplifier output power was within the $TEM_{0,0}$ mode. The measurement of the RIN showed that the amplifier added less than an order of magnitude to the noise of the seed laser source.

Altogether we demonstrated that the presented laser design is suitable as laser source for gravitational wave detectors as it meets the free running laser specifications of the currently used laser systems.

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