Beam quality and noise properties of coherently combined ytterbium doped single frequency fiber amplifiers

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Abstract: Collinear coherent combination of multiple single frequency fiber amplifiers is a promising approach to realize the high power laser sources required for 3rd generation gravitational wave detectors (GWD), as long as the stringent requirements on the beam quality and noise properties can be met. Here, we report the beam quality and noise properties of two coherently combined 10 W single frequency amplifiers with respect to the requirements of GWD. The combining efficiency was larger than 95% with 97% of the combined beam in the fundamental spatial mode. There was no significant noise increase compared to the fluctuations of the single amplifier.

OCIS codes: (230.2285) Fiber devices and optical amplifiers; (140.3425) Laser stabilization.

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1. Introduction

The 3rd generation of gravitational wave detectors will most likely require single frequency TEM_{00} laser sources at 1064 nm with output power in the kW range [1]. A promising approach to achieve these output power levels are master-oscillator fiber-amplifier systems employing a stable low power single frequency source and multiple fiber amplifier stages to increase the power. Currently, single frequency fiber amplifiers up to 500 W have been reported [2–4]. Scaling the power above this level becomes increasingly difficult due to Brillouin scattering and thermal effects.

One possibility to avoid these difficulties is to use two or more amplifiers and to coherently combine their output beams. In recent years, many improvements were reported in this field [5–11]. For gravitational wave detectors a narrow linewidth is required. Conveniently, this narrow linewidth is also extremely beneficial for coherent beam combining. For use in gravitational wave detectors the resulting beam has to be close to the diffraction limit, because only the power in the fundamental Gaussian mode can be used in the resonant cavities utilized by the interferometer. Therefore, the combined beams must overlap in both near and far field. Thus a tiled aperture approach is not an option.

Previously, two collinearly combined injection locked Nd:YAG oscillators with an output power of 3 W each were investigated in terms of power and phase noise by Musha et al. [12] and three Raman amplifiers were collinearly combined for use in a frequency doubling cavity by Taylor et al. [13]. Uberna et al. proposed the use of polarizers [14] for collinear coherent combining. Here, we investigate collinear combining in a Mach-Zehnder configuration using two 10 W ytterbium doped fiber amplifiers seeded by a single-frequency Nd:YAG nonplanar ring oscillator (NPRO). We concentrate our investigations on power and frequency noise and the achievable beam quality.

2. Setup

We amplified an NPRO with an output power of 600 mW. The seed power was divided using a 50:50 beam splitter as depicted in Fig. 1. Each of the separated beams was amplified in a 4 m long double clad polarization maintaining ytterbium doped fiber (Nufern PLMA-YDF-10/125). Both amplifiers were co-pumped by a fiber coupled 25 W, 976 nm pump diode. With each amplifier we achieved an output power of 11.4 W and a polarization extinction ratio (PER) of 16-18 dB. To combine the two beams with the best possible beam quality and combining efficiency, we used a free space 50:50 beam splitter. Therefore, the beam combination is realized in a Mach-Zehnder configuration with one amplifier in each arm. We assume that the majority of the effects will be similar for high power amplifiers and so our setup should be a realistic prototype to demonstrate the concept and to learn about associated challenges.

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To stabilize the relative phase between both interferometer arms, we used a standard heterodyne technique. An electro optic phase modulator (EOM) in one interferometer arm induced 12 MHz phase modulation sidebands. These sidebands were used as phase references in a heterodyne readout scheme to measure the relative phase between the two interfering light fields on the combining beam splitter. A mirror mounted on a piezo electric transducer was placed in the other arm to stabilize this phase and to achieve stable interference of the two amplified beams. In the interferometer control loop the unity gain frequency was at 7 kHz.

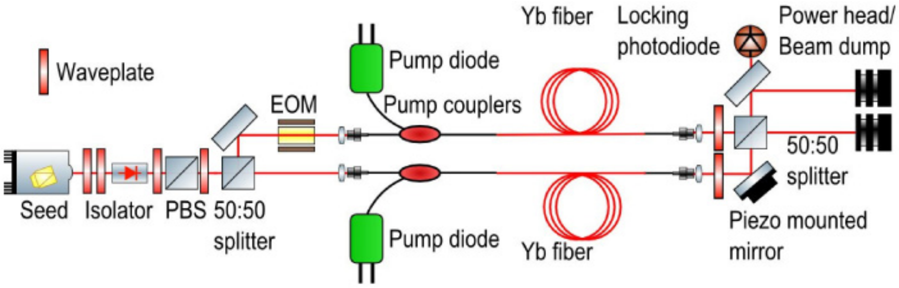

Fig. 1. Schematical overview of the beam combining setup. PBS: Polarizing beam splitter, EOM: electro optical modulator.

After measuring the output power of each amplifier (Fig. 2, triangles), we combined the two beams with a combining efficiency of 95-97% over the whole amplifier slope (Fig. 2, squares). During the measurement we fine-tuned the pump power of one amplifier to maximize the combining efficiency. At a pump power of 16 W per amplifier, the combined signal power was 21.8 W. Only 0.88 W left through the dark port of the interferometer. The impact of beam imperfections on the combining efficiency was discussed by Goodno et al. [15]. In our experiment the main contribution was polarization mismatch between both beams.

The system was stable under laboratory conditions and the duration of continuous operation was limited by actuator range. After a warm-up time of a few minutes the system stayed at its operation point for more than half an hour. It was possible to cause a relock with intentional flicks to the fiber or a knock on the optical table. Even though the long term performance was sufficient for our characterization the employment of a long range actuator for the interferometer control could increase the continuous operation time significantly.

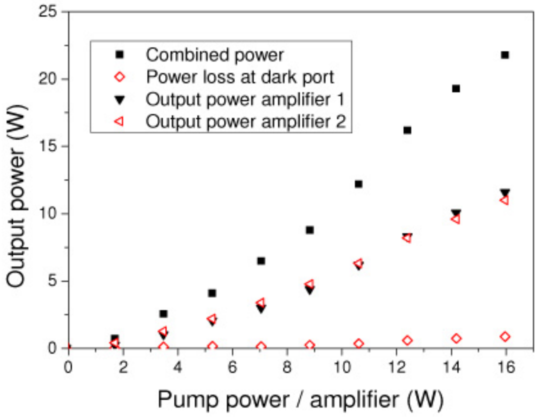

Fig. 2. Power of the amplifiers and the coherently combined output power of the system. When we measured the slope of the combined beam, the pump power of the second amplifier was fine tuned to optimize the combining efficiency.

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3. Beam quality

To evaluate the beam quality, we used a non-confocal three mirror ring cavity with non-degenerate TEM_{nm} eigenmodes (mode-cleaner cavity) [16] in a setup as depicted in Fig. 3. By scanning the cavity length over one free spectral range, the power in the different spatial modes can be separated and the power fraction in the fundamental Gaussian mode can be obtained. First, both amplifiers were individually mode matched to the cavity. This procedure also ensures a good spatial overlap between the two beams at the combination beam splitter and therefore aids a good combining efficiency. We then scanned the length of the resonator and measured the power at the reflecting port with a photodiode. From the ratio of the reflected power when the cavity was resonant for TEM_{00} and the power reflected by the non-resonant cavity, we obtained the power fraction in TEM_{00}. We deduced a TEM_{00} fraction of 97% for the single amplifiers as well as for the coherently combined beam. As neither the single amplifiers nor the combined beam was in a pure linear polarization state (16-18 dB PER) and since the mode cleaner cavity's resonance condition is polarization dependent, the remaining 3% were most likely dominated by TEM_{00} light in the second polarization state.

Furthermore, we used the 12 MHz sidebands already present in the combined beam to lock the cavity to the fundamental mode using the Pound-Drever-Hall technique [17, 18]. In this way we obtained a linearly polarized, pure Gaussian beam with an output power of 21.3 W in transmission of the cavity and 0.72 W reflected, consisting of TEM_{00} light in the second polarization state and higher order modes. This value is consistent with the 97% we obtained from scanning the cavity. These results show that a well aligned collinear beam combination does not degrade the beam quality.

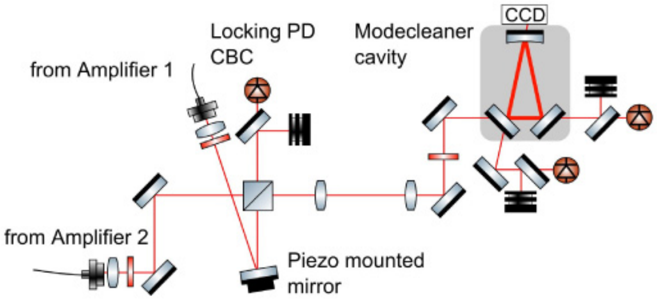

Fig. 3. Combining part of the setup, including the mode cleaner cavity for the beam quality measurement.

4. Power and frequency noise

To measure the power noise we used the beam transmitted by a mirror between the combining beam splitter and the mode cleaner cavity. Since we are interested in the noise properties of a linearly polarized output beam, we added a polarizing beam splitter cube in front of the highly reflective mirror (not shown in Fig. 3). We then measured the noise spectra of the single amplifiers as well as of the combined beam by means of a low noise photodetector.

In Fig. 4 the relative power noise (RPN) of the NPRO (green), a single amplifier (red), and the combined beam (black) are shown. In the frequency range from 1 to 1000 Hz the RPN of the single amplifier is significantly increased compared to the seed. The reason for this is most probably coupling of pump light power noise into the amplifiers output [19]. Since different pump diodes have different levels of RPN, the amplifiers had different RPN as well. The amplifier shown in Fig. 4 is the one with the larger RPN. For frequencies above 10 kHz the amplifier's RPN was dominated by the seed noise.

As shown in Fig. 4, the RPN of the combined beam is very close to the RPN of a single amplifier. For frequencies larger than 10 kHz the power noise is dominated by the seed source, such that it should be possible to reduce the RPN of the combined beam in this frequency range to a level below $10^{-6}\ \mathrm{Hz}^{-1/2}$ with a more stable seed source.

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The combined beam's power noise spectrum reveals an additional peak at approximately 15 Hz and some excess noise in the region of 100 Hz. Except for these few distinct peaks there is no power noise added by the beam combining, which is a quite promising result.

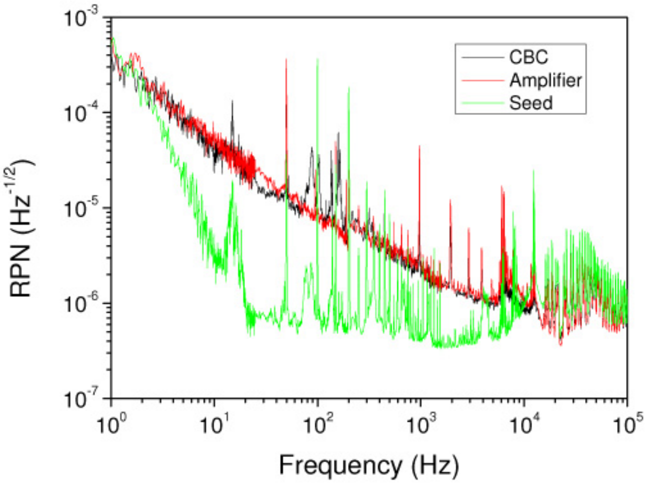

Fig. 4. Relative power noise of combined beam, single amplifier and NPRO seed laser. For the largest part of the spectrum the RPN is dominated by the single amplifiers.

To measure the frequency noise, we stabilized the mode cleaner cavity to the fundamental mode as described in section 3 and used the calibrated piezo control signal and the calibrated Pound-Drever-Hall error signal. From earlier measurement we know that the length noise of the cavity causes equivalent frequency noise smaller than the level measured here. As one can see in Fig. 5, the frequency noise is almost identical for both, the combined beam and the single amplifier. The measured 1/f slope is characteristic for the seed source [20]. The 15 Hz bump is probably caused by the seed laser as it is visible in the RPN of the NPRO as well.

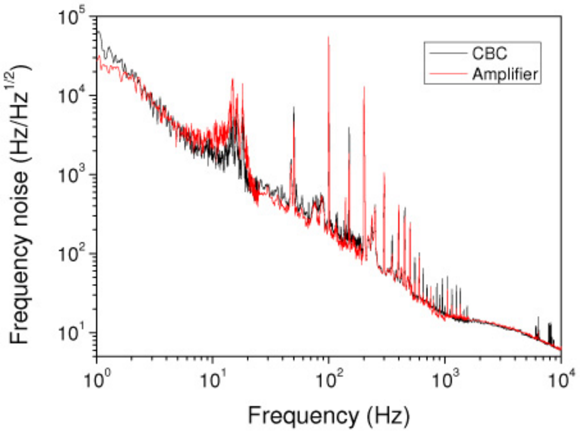

Fig. 5. Frequency noise of single amplifier and combined beam.

For a better understanding of the dynamics and the origin of the small additional noise features in the combined beam, we monitored actuator- and error signal of the interferometer control loop. From these signals, we derived the free running differential phase noise (see black curve in Fig. 6) and the in-loop stabilized phase noise (Fig. 6, blue curve). As the arm lengths were only balanced to a length difference of about 1 m, frequency noise of the seed laser couples into differential phase noise. The magnitude of this effect was calculated by projecting the single amplifiers frequency noise to the interferometers phase noise and is shown in Fig. 6 (red curve). It can be seen that the phase noise measurement is not influenced by the frequency noise of the seed laser.

The additional peaks in the power noise spectrum are also present in the differential phase noise of the interferometer. They could be caused by mechanical or electrical disturbances of the interferometer.

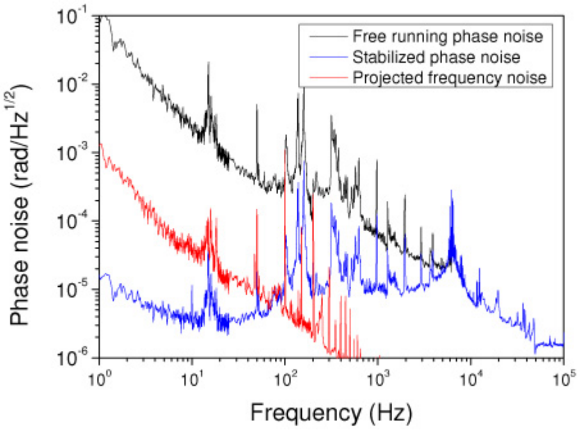

Fig. 6. Differential phase noise of the two amplifiers (free running, stabilized and the projection of frequency noise of the seed laser). The peak at ~15 Hz and the ones around 100 Hz, which can be seen in the RPN of the combined beams, are also present here.

Neglecting the distinct peaks in the spectrum, we can approximate the free-running phase noise power spectral density as $S_\varphi = 10^{-1}\,\mathrm{rad}\sqrt{\mathrm{Hz}}\,/\,f$. In a phase locked system with a control loop gain $\sim 1/f$ this noise becomes approximately constant for frequencies lower than unity gain frequency. The phase variance $<\varphi^2>$ in dependence of the unity gain frequency can then be obtained by integration of S_φ^2 from unity gain frequency to infinity and adding the integrated constant noise below unity gain. This results in $<\varphi^2> = 2\cdot 10^{-2}\,\mathrm{rad}^2\mathrm{Hz}\,/\,f_u$. With this, the contribution of the phase variance to the combining loss can be estimated. For example, to keep this contribution below 1%, we need $<\varphi^2> \leq 4\cdot 10^{-2}\,\mathrm{rad}^2$, i.e. a unity gain frequency above 0.5 Hz would be sufficient.

However, to avoid the coupling of the 15 Hz peak to power noise and to increase the overall system stability, one should include it in the control loop bandwidth. A unity gain frequency of less than 100 Hz will still be sufficient for this. Thus, even a very simple interferometer control loop can fulfill these moderate requirements.

5. Summary and outlook

We demonstrated collinear coherent beam combining at 1064 nm using two ytterbium doped fiber amplifiers. We achieved a combining efficiency larger than 95% and a combined power of 21.8 W. The setup was stable under laboratory conditions and the long term performance was limited by the available range of the length control actuator of the interferometer. 97% of the output power was emitted into the fundamental Gaussian mode. This high spatial quality is well within the typical GWD requirement of less than 5% in higher order spatial modes. Apart from some small additional peaks, the RPN was dominated by the single amplifiers. Even though the free running noise level of the combined beam is much higher than the GWD RPN requirement of several 10^{-9} Hz$^{-1/2}$ it is slightly smaller than the noise level of solid state lasers currently used in GWD experiments [21]. To improve the power stability, the controllability of the power fluctuations is an important design requirement. In our beam combining layout the power can be controlled by a combined feedback to the pump light of both amplifiers. Slow separate control of the pump power of each amplifier will be required anyway, to compensate for power drifts of the interfering beams which would otherwise reduce the contrast of the interferometer. In terms of frequency noise we found almost no difference between a single amplifier and the combined beam. This frequency noise is dominated by the seed laser which has been shown to be controllable to the stability level required by GWDs [22].

When combining high power fiber amplifiers, potentially more thermally and gain induced phase noise will have to be compensated. However, it has already been shown that differential phase stabilization is possible even at the kW power level. Since the fibers used in high power amplifiers are not strictly single mode, combining efficiency and fundamental mode content will likely degrade compared with the single mode fibers we used in these experiments. The influence of beam pointing might also be more significant in high power amplifiers, which could degrade the combining efficiency and therefore contribute to the power noise.

Overall, we conclude that beam combining is a promising approach to realize the laser sources to be used in 3rd generation gravitational wave detectors.

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