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.

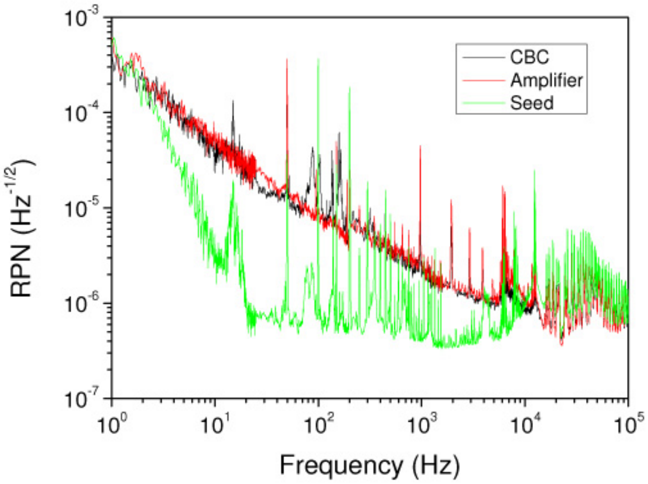

Fig. 4. Relative power noise of combined beam, single amplifier and NPRO seed laser. For the largest part of the spectrum the RPN is dominated by the single amplifiers.

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.

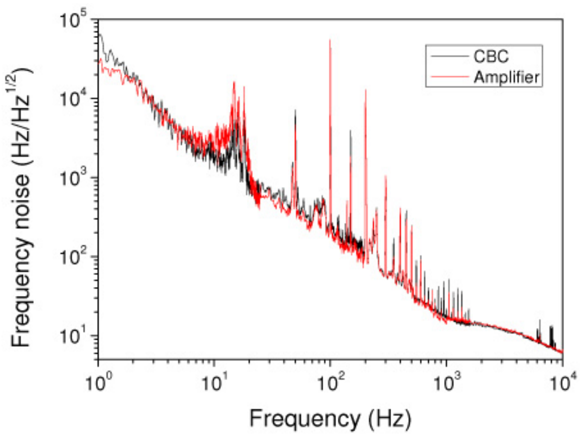

Fig. 5. Frequency noise of single amplifier and combined beam.

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.

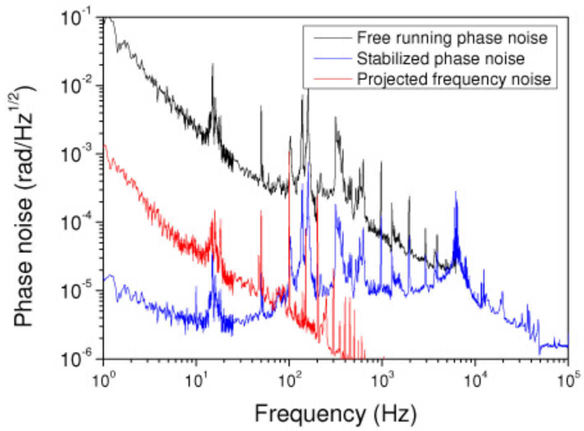

Fig. 6. Differential phase noise of the two amplifiers (free running, stabilized and the projection of frequency noise of the seed laser). The peak at ~15 Hz and the ones around 100 Hz, which can be seen in the RPN of the combined beams, are also present here.

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 $10^{-9}\,\mathrm{Hz}^{-1/2}$ 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

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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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