All-fiber coherent beam combining with phase stabilization via differential pump power control

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Received January 4, 2012; revised February 14, 2012; accepted February 20, 2012;
posted February 21, 2012 (Doc. ID 160910); published March 26, 2012

Coherent beam combining enables power scaling beyond the limits of single amplifiers. Therefore, improving the performance and simplicity of coherent combination techniques is of great interest for many high power applications. Here, we show all-fiber coherent beam combining of two ytterbium doped amplifiers with and without a dedicated phase actuator and a total output power up to 25 W. Instead of a dedicated phase actuator, we directly controlled the two ytterbium amplifiers to also stabilize their relative phase. We compared the performance of this method with phase stabilization using two piezo driven fiber stretchers. In both cases, power noise was dominated by the single amplifier. © 2012 Optical Society of America

OCIS codes: 230.2285, 140.3425.

In recent years coherent beam combining (CBC) has become the most prominent means of brightness scaling. Its scalability beyond the usual single amplifier limits due to nonlinearities or thermal effects enables kilowatt class single frequency sources [1] and generation of high energy pulses [2,3]. Because beam quality and noise properties of a single amplifier can be preserved, it is a promising concept for the laser source for third generation gravitational wave detectors [4]. Nevertheless, a major drawback of these systems is the increased complexity due to the multiple paths, required control loops, and actuators.

The most obvious step towards a more simple setup is moving to an all-fiber configuration. This eliminates the need for mode matching of the output beams to each other and potentially reduces the sensitivity to environmental noise. Naturally, this introduces new challenges as well, as the power handling capabilities of fiber components are often not as good as for their free space counterparts. For example, piezo mounted mirrors can be replaced with piezo driven fiber stretchers, but these require comparatively long fiber lengths, which can cause problems due to nonlinear effects. In the past, erbium fiber amplifiers have been used as phase actuators at the ytterbium wavelength, and vice versa [5,6]. This method is based on the refractive index changes due to heat load and via Kramers–Kronik relations in the additional amplifier and does not rely on any mechanical parts nor require any high voltage sources. It is also capable of handling high power levels, because it is a true all-fiber method with low insertion loss. However, like fiber stretchers, it will add some additional fiber length, and the actuator range depends on the number of contributing ions. Therefore, for beam combining at the ytterbium wavelength, a medium power erbium fiber amplifier would be required as well, which would make the overall system neither simple nor cost effective. However, when operating at medium or higher average power, differential phase stabilization via direct pump power modulation of the power amplifiers as proposed by Minden [7] becomes a viable option, thus eliminating the need for a dedicated phase actuator altogether.

The penalty for this approach is conversion of phase drifts to power noise. Assuming perfectly matching phases in the combining element, coherent addition of two fields with a small modulation ($A_1 + \Delta A_1$ and $A_2 + \Delta A_2$) yields the output power at the bright/dark port

$$P = \frac{1}{2}((A_1 + \Delta A_1) \pm (A_2 + \Delta A_2))^2. \qquad (1)$$

If both mean fields are the same ($A_1 = A_2 = A = \sqrt{P}$) and only amplifier 1 is modulated to compensate the phase drift ($\Delta A_1 = \Delta A$, $\Delta A_2 = 0$), the total power is $P_{\mathrm{bright}} \approx 2A^2 + 2A\Delta A = 2P + \Delta P$. If instead of using one amplifier both amplifiers are controlled differentially ($\Delta A_1 = -\Delta A_2 = \Delta A$), there is no coupling to the bright port at all ($P_{\mathrm{bright}} = 2A^2$), and power modulation is only present at the dark port ($P_{\mathrm{dark}} = 2\Delta A^2$). Unfortunately, a linear controller will usually control the power and not the field, which adds a second order combining loss term to the bright port. However, differential pump power control is still a significant improvement over the linear coupling in the single amplifier case. Assuming the induced phase shift to be linear with the output power ($\Delta P \propto \Delta\phi$) and the majority of the phase noise to be caused by environmental effects, the relative power noise (RPN) induced by phase stabilization decreases with average power, for both methods.

In our experiment, we coherently combined two 10 W class ytterbium doped fiber amplifiers in an all-fiber configuration using either fiber stretchers or differential pump power control to stabilize the relative phase. The amplifiers were seeded by a nonplanar ring oscillator (NPRO) with an output power of 600 mW. The seed beam was coupled into the fiber, and the power was divided using a commercial 50 : 50 polarization maintaining (PM) fused coupler (Fig. 1(a)). The separated beams were amplified in 4 m long double clad ytterbium doped fibers (Nufern PLMA-YDF-10/125). Both amplifiers were forward cladding-pumped by a fiber coupled 25 W, 976 nm

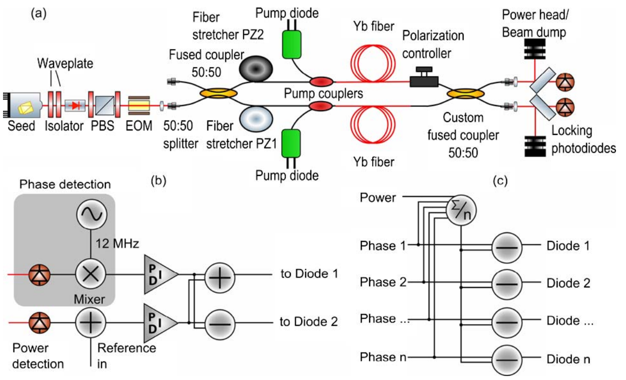

Fig. 1. (Color online) All-fiber CBC setup and stabilization via pump power modulation; (a) optical setup, (b) control path implementation in our setup, (c) possible extension to n amplifiers.

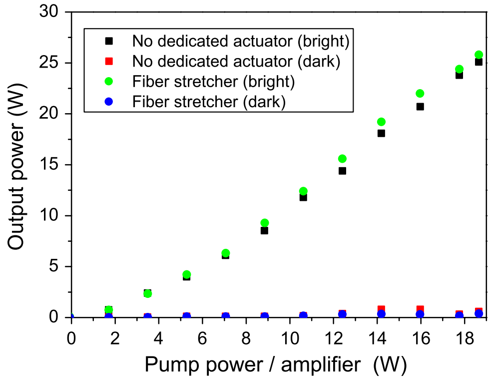

Fig. 2. (Color online) Slope for both actuation methods.

pump diode. For good beam quality, we had to use a filled aperture combining element [8,9]. To keep even this stage fiber based, we chose a fused coupler. To avoid stimulated Brillouin scattering in the coupler and the associated fiber, we used a custom homemade single mode non-PM fused coupler with a 10 μm core diameter, which can tolerate more than 25 W of output power [10]. It was the only non-PM component in the setup. For phase stabilization, we either used fiber stretchers (Optiphase, types PZ1 and PZ2) or amplifier pump power modulation.

The error signal for the differential phase control was generated with a heterodyne readout scheme. For this, an electro optic modulator (EOM) added 12 MHz frequency sidebands to the seed beam before it entered the CBC setup. Because of the arm length difference between both beam paths (~30 m), these sidebands could be used as a phase reference for the heterodyne readout scheme to measure the relative phase of the two interfering fields in the coupler. The EOM was only used to add the sidebands; therefore the system would work without the EOM when using a different method for the phase readout. For phase control with the fiber stretchers, this error signal was used to control the faster fiber stretcher (PZ1), while the slow stretcher (PZ2) kept PZ1 in a center position.

When using pump power control instead, we generated the differential control signal with a combination of an analog adder and a subtractor (Fig. 1(b)) and fed the result back to the pump diodes. When inverting the sign of the control signal for one pump diode, the phase can be controlled (asymmetric path). The power can be stabilized simultaneously by feeding the same signal to both pump diodes (symmetric path). This concept can be scaled by stacking up 2^n amplifiers, but also with a $1 \times N$-combiner and summation over all control signals for a first order feed-forward power correction, as shown in Fig. 1(c). One could argue that this feed-forward control is not necessary when stabilizing the power anyway, but the reduced cross coupling between phase and power stabilization will be beneficial when optimizing the feedback loops. Because of the current supply we used, we were limited to a unity gain frequency of 1 kHz. This was lower than the bandwidth of the fiber stretcher control loop (≈9 kHz), but it should be possible to reach a comparable control bandwidth with more optimized electronics.

With both schemes, we achieved up to 25 W at the bright and less than 0.6 W at the dark port (Fig. 2). Over the whole amplifier slope, the power loss at the dark port was less than 5%. It was even possible to keep the system in lock while increasing the pump power from 0 W to 18 W when using the fiber stretchers, which can change the optical path in the mm range. Naturally, this was not possible when using the amplifiers as phase actuators. Furthermore, one has to note that the combining efficiency eventually becomes worse when using the amplifiers to stabilize the phase, as the average power imbalance increases with time. However, the bright port usually stayed within 5% of the operating power, even when locking for half an hour or more, and the combining efficiency can easily be reset to the optimum value by allowing for a short relock. Nevertheless, for long term operation without any relocks, an additional actuator would be recommended. Even a simple thermal actuator such as a Peltier element should be sufficient.

In Fig. 3, the RPN of the system using fiber stretchers (red) and pump power modulation (black) is shown. In the frequency range from 1–10 kHz, the performance of the fiber stretcher based control loop is about a factor of 2 better. When stabilizing the phase using the ytterbium amplifiers, the unity gain frequency was 1 kHz, so this region is not in the control loop bandwidth. Overall, the noise is mostly limited by the single amplifier noise, which was also the case in our free space system [4]. This is quite surprising considering the pump stabilization scheme converts phase noise to power noise. Yet, the low fractional pump power modulation required to compensate the phase drifts and the differential pump power stabilization scheme prevent the power noise from increasing above the level of a single amplifier.

Because the power noise is dominated by the single amplifier, we compared the conversion of phase noise to power noise for direct pump modulation of one amplifier and differential pump power modulation by injecting a frequency dependent phase modulation into the setup. Since there is no linear coupling in the differential stabilization scheme, there should be a large difference in phase noise to power noise coupling between the two locking schemes. We induced the phase modulation using the PZ1 fiber stretcher and monitored the resulting modulation of the output power. A frequency dependent

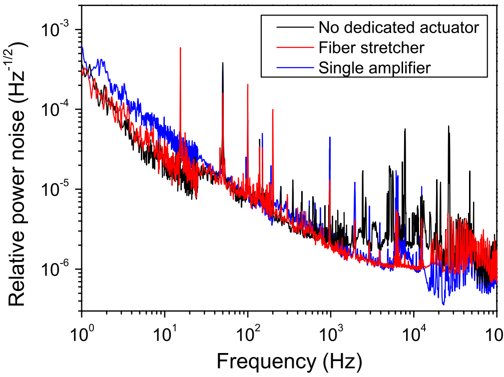

Fig. 3. (Color online) RPN in the frequency range from 1 Hz to 100 kHz.

plot of the induced relative power modulation divided by the driving phase modulation is shown in Fig. 4. Since the unity gain frequency was 1 kHz in the control loop, the performance was similar above this frequency. For lower frequencies, the difference quickly becomes more than 1 order of magnitude, demonstrating the improvement due to the differential pump power control.

We have demonstrated all-fiber CBC of two ytterbium doped amplifiers with a total output power of up to 25 W. The power noise in the frequency range from 1 Hz–100 kHz was comparable to the single amplifier RPN even when using the power amplifiers as phase actuators. Therefore for short to medium time operation, it is a viable option to lock the CBC systems in this way. This phase control method should also be scalable to higher output power, since the inducible phase shift increases with average power.

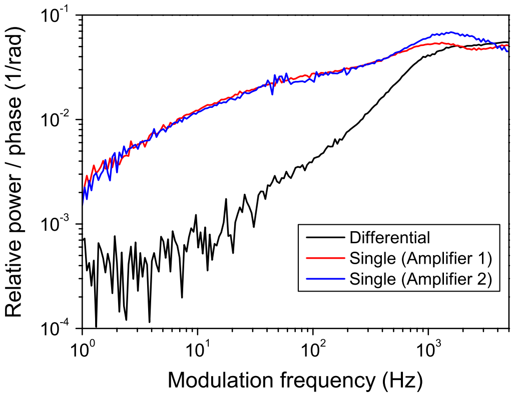

Fig. 4. (Color online) Noise coupling from phase to power noise with the differential and single amplifier stabilization.

We would like to thank Jan Hendrik Pöld and Benno Willke (Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Institut für Gravitationsphysik, Leibniz Universität Hannover) for our collaboration on the free space system, as well as Thomas Theeg and Katharina Hausmann for the custom fused coupler. This research was made possible by the Cluster of Excellence Centre for Quantum Engineering and Space-Time Research (QUEST) funded by the German Research Foundation (DFG). H. Tünnermann acknowledges a Ph.D. grant from the Hannover School for Laser, Optics and Space-Time Research (HALOSTAR) and Y. Feng would like to thank QUEST for supporting his stay at the Laser Zentrum Hannover e.V. as a visiting scientist.

References

1. A. Flores, T. M. Shay, C. A. Lu, C. Robin, B. Pulford, A. D. Sanchez, D. W. Hult, and K. B. Rowland, in *CLEO* (2011), paper CFE3.
2. E. Seise, A. Klenke, S. Breitkopf, J. Limpert, and A. Tünnermann, Opt. Lett. **36**, 3858 (2011).
3. L. Daniault, M. Hanna, L. Lombard, Y. Zaouter, E. Mottay, D. Goular, P. Bourdon, F. Druon, and P. Georges, Opt. Lett. **36**, 621 (2011).
4. H. Tünnermann, J. H. Pöld, J. Neumann, D. Kracht, B. Willke, and P. Weßels, Opt. Express **19**, 19600 (2011).
5. A. A. Fotiadi, N. Zakharov, O. L. Antipov, and P. Mégret, Opt. Lett. **34**, 3574 (2009).
6. H. Tünnermann, J. Neumann, D. Kracht, and Peter Weßels, Opt. Lett. **36**, 448 (2011).
7. M. Minden, "Phase control mechanism for coherent fiber amplifier arrays," U.S. patent 6,400,871 (June 4, 2002).
8. E. C. Cheung, J. G. Ho, G. D. Goodno, R. R. Rice, J. Rothenberg, P. Thielen, M. Weber, and M. Wickham, Opt. Lett. **33**, 354 (2008).
9. R. Uberna, A. Bratcher, T. G. Alley, A. D. Sanchez, A. S. Flores, and B. Pulford, Opt. Express **18**, 13547 (2010).
10. T. Theeg, K. Hausmann, M. Frede, H. Sayinc, J. Neumann, and D. Kracht, in *CLEO/Europe and EQEC* (2011), paper CJ2_1.