EPJ Web of Conferences **307**, 02016 (2024) https://doi.org/10.1051/epjconf/202430702016
EUROPHOTON 2024

Low differential phase noise ytterbium-doped fiber amplifier system for coherent beam combination

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Abstract

A two-channel ytterbium-doped fiber amplifier system with active phase-locking reaches a differential phase noise of only 40 mrad (λ/160) at 200-W channel power. Frequencies above 30 Hz did not require noise suppression, thus simplifying advanced beam-shaping through coherent beam combination.

1. Introduction

Coherent beam combination (CBC) is a leading approach for the power-scaling of laser sources [1]. Several types of CBC exist, including tiled and stacked aperture, as well as active and passive phase control. Most research uses Yb-doped fiber amplifiers and targets high brightness with (nearly) diffraction-limited output beams, but tiled apertures with active phasing also opens up for control of the beam shape [2]. This is attractive for commercial applications such as materials processing. However, combining multiple elemental beams introduces challenges in controlling the spatial intensity profile of the combined beam because of the phase noise, especially in fiber amplifiers dealing with high intensities and significant thermal effects. Consequently, there is significant interest in developing methods for detecting and controlling the relative phase of each elemental beam, in a way that allows for sophisticated and versatile beam-shape control and also meets the cost constraints of commercial applications. Thus, the study of high-power fiber amplifiers with low relative (differential) phase noise is essential for CBC. In this article, we present an ytterbium-doped fiber amplifier system designed to reduce differential phase noise, targeting coherent beam combining with beam-shaping. Experimentally, we have developed a two-channel YDFA system with 200-W channel power and differential phase noise as low as 40 mrad (λ/160), showcasing its potential for high-power CBC applications.

2. Experimental

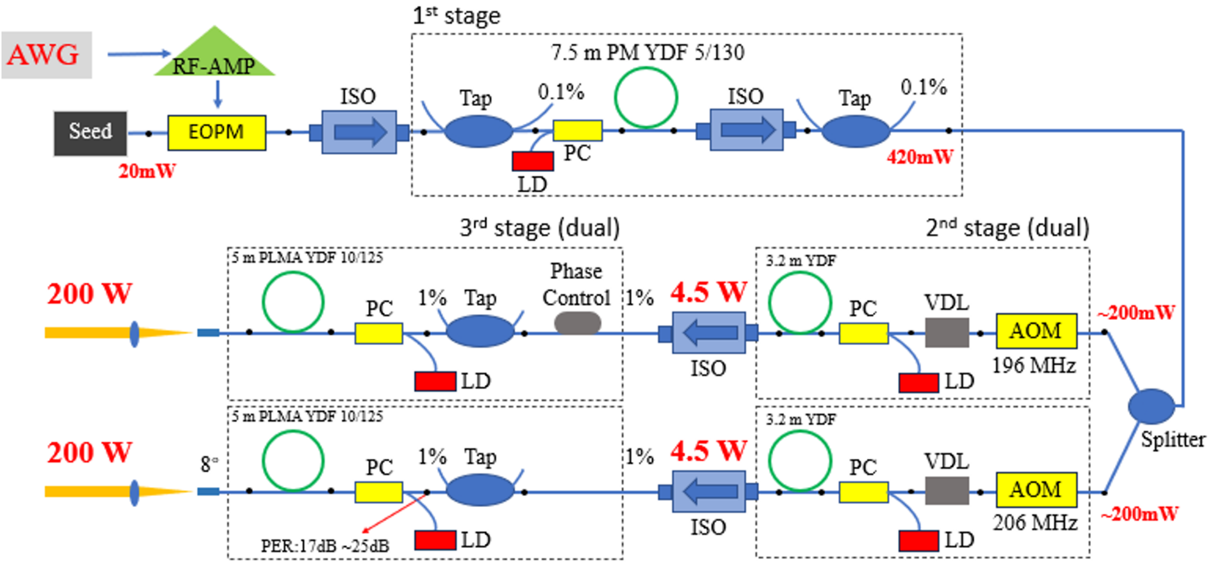

Fig. 1 Schematic of amplifier system.

The system (see Fig. 1) is seeded by a single-frequency Yb-doped fiber laser (Koheras ADJUSTIK Y10) emitting 20 mW of output power at a wavelength of 1070 nm. This is amplified to 420 mW, which is subsequently split to and amplified in two parallel arms. To suppress stimulated Brillouin scattering (SBS), the seed is broadened using an electro-optic phase modulator (EOPM), driven by the amplified output from an arbitrary waveform generator (Tektronix AWG710), set to generate samples with random amplitude noise. Two acousto-optic modulators (AOMs, Gouch & Housego PM FIBER-Q) are driven by amplified sinewave generators at 196 and 206 MHz to frequency-shift the lightwaves and yield a differential beating frequency of 10 MHz for heterodyning. This intermediate frequency worked well for phase-noise retrieval through heterodyning. Alternatively, the AOMs could be set to the same frequency for homodyning. Additionally, the path lengths of the amplifiers are matched within the coherence length of the broadened lightwave through the use of variable delay lines (VDLs). All fibers in the signal path is polarization- maintaining. The combined output beam of the two channels is sampled by a detector. The detected beat signal can then be used for locking the differential phase of the two beams by means of a piezo-electric fiber stretcher in one of the arms (channel 1). It can also be used for phase-noise calculations, for which we captured temporal traces with an oscilloscope (Agilent Infiniium DSO9104H). The phase noise was also measured by a signal analyzer (Agilent N9020A).

3. Results

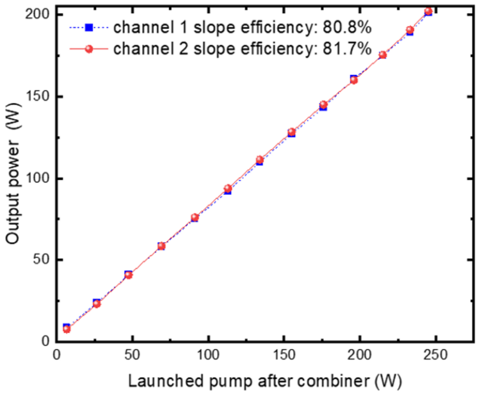

Fig. 2. Output power vs. launched pump power for the last-stage YDFAs in the two channels.

The final-stage YDFAs achieved an output power of 200 W each, with a slope efficiency of 80%, see Fig. 2. In the phase-locked state, the differential phase noise was 40 mrad RMS, as integrated from 100 Hz to infinity (Fig.3). This allows for CBC with a minimal combination penalty of 0.16%. The suppression for frequencies above 30 Hz is negligible. The low differential phase noise achieved is indicative of the system's robustness and its potential for high-power applications requiring precise beam shaping. In addition, the lock/unlock phase are recorded, and both of the integrated phase noise are shown. The total phase noise (integrated over all frequencies except the DC component) decreases from 620 mrad to 40 mrad, through the phase-locking. As next steps, we will add channels and demonstrate beam-shaping.

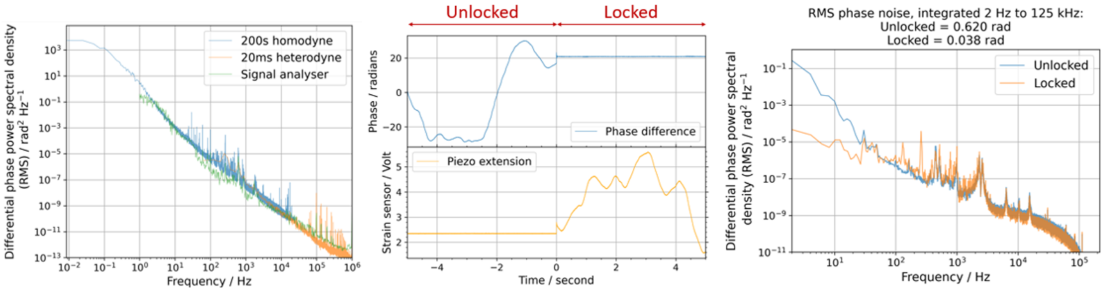

Fig. 3. Phase trace and PSD characterization.

This work is funded by EPSRC (EP/W028786/1, Smart Fibre Optics High-Power Photonics “HiPPo”). Data availability a http://doi.org/10.5258/SOTON/D3038

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[2] Ben Mills, James A. Grant-Jacob, Matthew Praeger, Robert W. Eason, Johan Nilsson & Michalis N. Zervas , "Single step phase optimisation for coherent beam combination using deep learning", Sci Rep 12, 5188 (2022).