Neural Network Coherent Beam Combination with Low Differential Phase Noise Ytterbium Fiber Amplifiers

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Abstract: Parallel two channel Yb-fiber amplifiers with low differential phase noise above 100 Hz, up to 200 W, were phase-locked for coherent beam combination using neural networks and principal component analysis, with lambda/120 stability at 900 cycles/s control. © 2024 The Authors

1. Introduction

Fiber laser sources with high power have become dominant in materials processing. However, the maximum power achievable from a single fiber core is limited by several material and nonlinear effects due the high intensities encountered, for example Stimulated Raman Scattering, Stimulated Brillouin Scattering (SBS), and the optical Kerr effect. While increasing the core size can help, it also lowers the threshold for transverse mode instability [1], which is undesirable. An alternative strategy to power scaling the fiber architecture is coherent beam combination (CBC) [2], where several fiber lasers are locked in phase to create a coherent wavefront, resulting in a higher power single source with beam-shaping agility. However, CBC requires precise control of the laser phases to ensure a stable and uniform combined spatial intensity profile, which can be a particular issue in fiber amplifiers dealing with high intensities and significant thermal effects. Consequently, there is significant interest in developing methods for recognizing and correcting the beam phases in real-time CBC.

The current channel count for fiber CBC is in the hundreds [3], and commercially available systems can deliver up to 28 kW and possibly considerably more [4]. As the channel number grows, the approaches to phase error correction face additional challenges in cost, complexity, and accuracy. Here, we tackle these problems using neural networks, which are uniquely suited to extracting information from complex datasets that are difficult to analyse with conventional tools [5,6]. A potential drawback is that the execution time of a neural network is typically slower than conventional electronics and algorithms. Here, we tackle this problem in two ways, by developing both low differential phase noise amplifiers and neural networks optimized for execution speed.

2. System Design

The system, see Fig. 1, uses a single-frequency diode laser that is amplified then split into parallel high-power final stage amplifiers. To suppress SBS the seed is broadened to 5 GHz using an electro-optic phase modulator (EOPM) seeded with pseudo-random noise from an arbitrary waveform generator (AWG). Two acousto-optic modulators (AOMs) perform frequency adjustments that facilitate homodyning/heterodyning techniques for construction and diagnostics. We ensure that the path lengths of the amplifiers are matched within the coherence length through variable delays (VDL). All fiber and components are polarization-maintaining. Phase measurement diagnostics supplementary to those shown in Fig. 1 were also used.
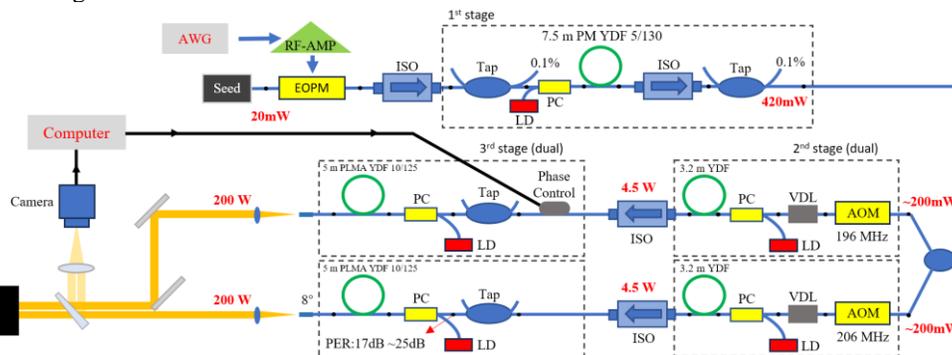

Fig.1 Fiber amplifier schematic and tiled beam combination with beam sampling to camera.

3. Results

The amplifiers achieved an output power of 200 W with an optical-optical efficiency of 80%. Through careful management of the intensity noise of the pumping diodes the system demonstrated a differential phase noise of 55

mrad RMS integrated from 100 Hz to 125 kHz, at 164 W, without any phase locking. Phase errors below 100 Hz are much larger in amplitude and must be actively suppressed for stable and accurate CBC, with a target total RMS error of below 100 mrad ($\lambda/63$).

We tested two neural network designs in a feedback loop to control and stabilize the differential phase of the amplifiers, using piezoelectric fiber stretchers for piston phase control in one amplifier. The neural networks were given images of the combined amplifier beams via a USB3-based CMOS camera, with the networks executed on a desktop PC. We first tested an artificial neural network using filled aperture combination that used the average combined beam intensity, operating initially at 30 W due to experimental considerations. The dual amplifiers under no locking and active locking are shown in Fig. 2. The locked region is clearly marked by the stable differential phase, with the piezoelectric stretcher actively compensating accumulated phase. The power spectral densities (PSDs) of the differential phase under both conditions are shown in Fig. 2. The phase error under active control was 52 mrad RMS, integrated from 3 Hz to 200 kHz, which is within tolerance for CBC applications. The control algorithm, including neural network computation, operated at 900 cycles/second, which effectively suppressed differential phase error below 100 Hz.
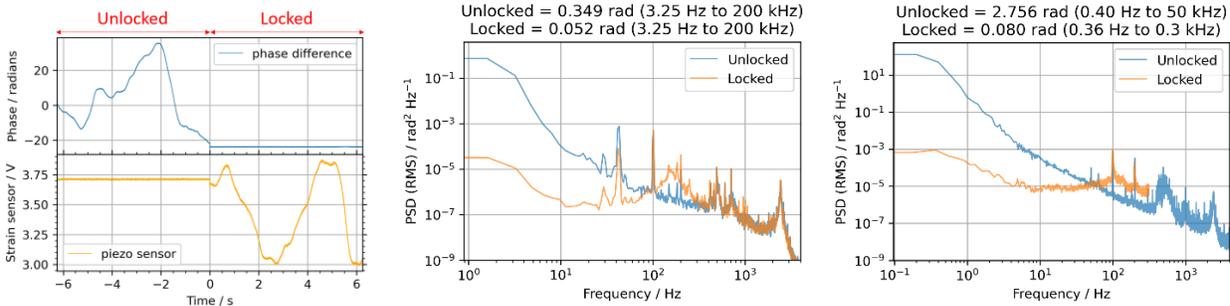

Fig.2 Stabilised phase trace and controller actuation, filled aperture phase PSD, and tiled aperture PSD.

The system was also implemented with tiled array CBC, placing each amplifier beam side-by-side. After focusing with a lens, we performed principal component analysis (PCA) on the combined beam image, which is a dimensionality reduction method that can reduce the input data quantity from 2x64x64 (reference and current image, 64x64 pixels) to the 25 most significant orthogonal vector basis set components. This reduces the data load into the neural network and can allow for faster operation due to a smaller network (25 inputs > 16 > 32 > 64 > 128 > 1 output, fully connected). The differential phase PSD is shown in Fig. 2. The control bandwidth was 600 cycles/s, slower than previously due to the additional PCA step and different network design, with an integrated phase error of 80 mrad.

We expect similar performance at 200 W output, once experimental limitations allow, and the proposed system is scalable with plans to expand to a seven-channel tiled array. At this point the neural network approach will become increasingly valuable, due to its ability to manage complex systems with a minimal increase to control scheme hardware and latency, and its potential for complex beam shaping other than just power in bucket. We have found through simulations that the PCA and neural network approach is scalable to additional channels, and through experiment that it had improved performance compared to directly inputting the beam image to the NN.

4. Summary

A two-channel ytterbium-doped fiber amplifier system with active phase-locking using neural networks reached a differential phase noise of only 52 mrad ($\lambda/120$) at 30 W channel power. Frequencies above 100 Hz did not require suppression. We show the effectiveness of principal component analysis (PCA) on input data prior to neural network operation, enabling reduced latency neural network implementation, the first time this approach has been used in this field, to our knowledge. Future work will focus on further power scaling of the design, implementing the control of additional output channels, and exploring beam-shaping capabilities.

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