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FPGA BASED OPTICAL PHASE CONTROL FOR COHERENT LASER PULSE STACKING *

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Abstract

Coherent temporal pulse stacking combines the energy from a train of pulses into one pulse through a series of optical cavities. To stabilize the output energy, the cavity roundtrip phases must be precisely locked to particular values. Leveraging the LLRF expertise we have for conventional accelerators, a FPGA-based control system has been developed for optical cavity phase control. A phase measurement method, "Modulated Impulse Response", has been developed and implemented on FPGA. An experiment demonstrated that it can measure and lock the optical phases of four stacking cavities, leading to combination of 25 pulses into one pulse with 1.5 % RMS stability over 30 hours.

INTRODUCTION

Nonlinear effects and optical damages are the most dominant factors impacting the extractable energy in a high intensity fiber amplifier [1]. A novel concept, coherent temporal pulse stacking, can overcome these limitations, by combining many pulses in a train passed through an amplifier into one single pulse using a series of Gires-Tournois interferometers [2]. However, the stacked output is sensitive to various perturbations, such as applied RF modulations, oscillator power, alignment stability [3]. To stabilize the output pulse energy, a real-time control system is required. In Berkeley Lab, we are trying to extend the LLRF control expertise we have for conventional accelerators to the optical cavity phase control for this scheme. One of the main parameters impacting the output energy is cavity roundtrip phases. A direct cavity phase detection, named as Modulated Impulse Response, has been developed for the Coherent Pulse Stacking.

A stacking experiment has been set up to demonstrate the control system we developed. Fig. 1 shows the concept, in which 25 equal amplitude pulses can be stacked into one pulse through two short cavities and two long cavities. In the first stage, the cavity length is one pulse period (1X), groups of five pulses are stacked, producing five pulses, separated by five pulse periods. In the second stage, the cavity length is five pulse periods (5X), which stack five pulses from previous stage into one final output pulse.

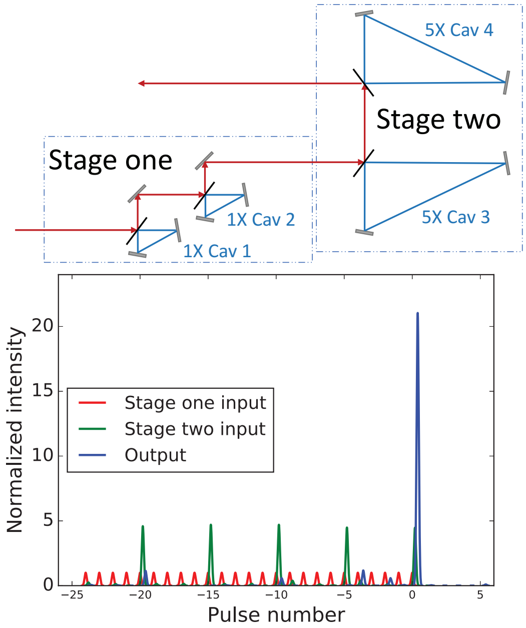

Figure 1: 25 equal-amplitude pulses can be stacked into one pulse with enhancement over 20 through two 1X cavities and two 5X cavities.

OPTICAL SETUP AND CONTROL DEVELOPMENT

The optical setup to demonstrate the two-stage stacking scheme is shown in Fig. 2. We use a SESAM mode-locked oscillator, which produces 1064 nm, 10 ps pulses at 400 MHz. The output is then coupled into fiber, and modulated in amplitude and phase with $LiNbO_3$ modulators and amplified in a Yb fiber amplifier. The amplified pulses are then directed into free space optical cavities.

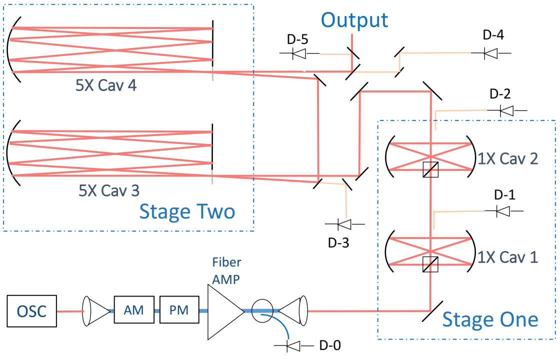

Figure 2: Optical setup of 25 pulse stacking experiment, showing pulse burst source and four optical cavities.

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Herriott-cell cavities are used for its exceptional stability [4]. A Herriott cell consists of two concave mirrors, placed on the same optical axis facing each other. For certain values of mirror radii and spacing, the output beam will return to the same path as it enters the cavity, with the same position, beam size and divergence, thus the profile overlapping is guaranteed. Two different designs are used. For the short 1X cavity, a beam splitter is placed between two mirrors. The laser beam enters the cavity through the cube, resulting in two bounces on each mirror. For the long 5X cavity, a similar folded design is adopted with a flat mirror at the center of the cavity. The flat mirror has a quarter of flat mirror coated for 50 % reflectivity and the rest for high reflectivity. There are four reflections of the beam per mirror, resulting in a compact design. After each cavity, one photodiode is installed capturing a small proportion of light for optical phase detection.

A FPGA based control system has been developed for the stacking experiment [5]. The Xilinx ML605 is the FPGA carrier with an FMC110 carrier board attached. The FMC110 board has two high-speed (1 GHz) ADCs and two DACs. An expansion board has been developed providing slow DAC signals for the piezo. The data flow is shown in Fig. 3. Six pulse signals detected by photodiodes are multiplexed onto two ADCs using analog switches. The two DACs are used to control amplitude and phase modulators.

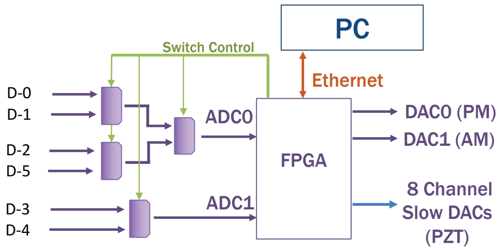

Figure 3: Data flow in the stacking controller.

MODULATED IMPULSE RESPONSE PHASE DETECTION

Several different phase detection algorithms have been investigated. Stochastic parallel gradient descent (SPDG) method has been shown in University of Michigan [6], which used a single peak power detector to measure the stacked pulse energy, while adjusting the cavity phases in a random manner to maximize the signal. However, the peak power detector did not measure each cavity phase directly. The convergence rate of the feedback became slower as the number of cavities increases. To avoid this limitation, a pulse pattern based phase locking method was developed [7], which used probe pulses to directly detect the optical cavity phase. However, the pulse pattern was not that stable, which made it difficult to measure all the cavity phases. An improved method based on the pulse pattern way is developed for Coherent Pulse Stacking. We name this method as "Modulated Impulse Response". In this method, we used probe pulse bursts, which consists of two equal amplitude pulses with phase difference θ to detect optical cavity phases.

$$\tilde{i_n} = \delta[n-1] + \delta[n]e^{j\theta}, \tag{1}$$

The first burst is defined as "in-phase" probe and the second burst with $\frac{\pi}{2}$ increase of phase modulation as "quadrature" probe, while their respective second output pulse intensities are in-phase and quadrature intensity signals to reconstruct the optical phase angle. It can be derived that the in-phase and quadrature signals are cosine and sine functions of the cavity phase. Fig. 4 (b) relates the in-phase and quadrature response to the cavity phase, showing a track of circle, with the angle with respect to the horizontal axis being the optical phase $\phi - \theta$.

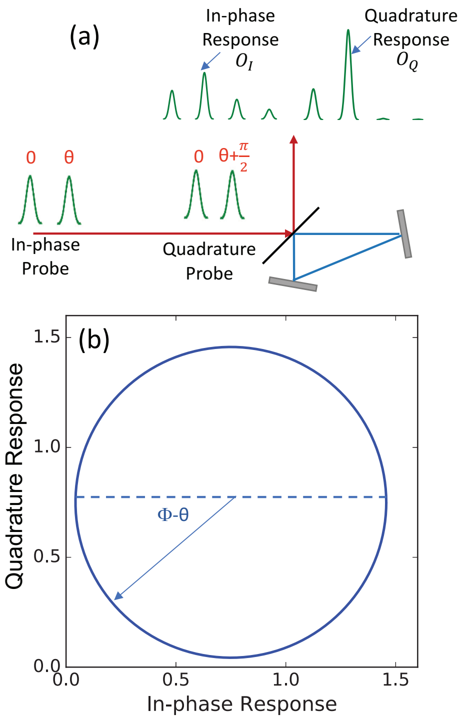

Figure 4: In-phase response vs quadrature response when probe burst is injected into an optical cavity.

The MIR concept can be easily extended to measure all the optical cavity phases in multi-cavity systems. And the algorithm has been implemented on FPGA based on standard CORDIC modules used in conventional accelerator control.

EXPERIMENT RESULT

All the cavity roundtrip phases in our experiment are measured with MIR method, and PI control loops are implemented to lock the optical cavity phases to certain values.

Fig. 5 compares a 5X cavity noise spectrum when control loop is open and when it is closed. Below 1 Hz, thermal drift is dominant, while above 1Hz, air turbulence and acoustic noise are the main perturbations. Above 500Hz, oscillator noise and electronic amplifier noise are the primary sources. The PI loop was operating at around 1.2 KHz, which helped

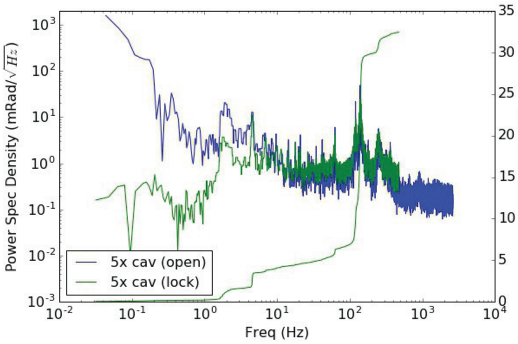

Figure 5: Phase noise spectrum comparison of 5X cavity between open loop and close loop case.

to eliminate thermal slopes in both cases. However, acoustic noise still had a considerable effect. Noise diagnostic shows that the remaining acoustic noise comes from the oscillator. The noise peak at 140 Hz, is due to this.

The MIR phase control method was used for the 25 pulse stacking experiment.Fig. 6 shows the experimental result. An energy enhancement of 18.4 was achieved compared with a theoretical value of 21.5. Ringing in the photodiode contributed to post pulse amplitude after the main pulse. One could see that the first-stage stacking operated well, five high intensity pulses were generated cleanly. However, there were large pre-pulses and post pulses with considerable intensity in second stage.

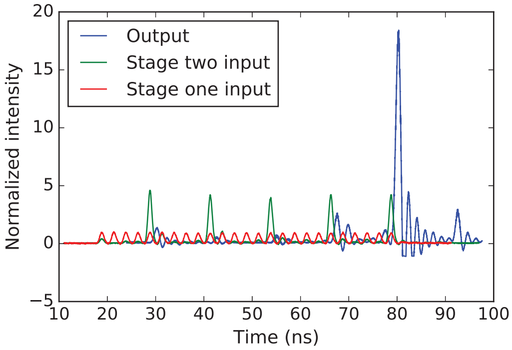

Figure 6: 25 pulse stacking experiment result. The output (blue curve), stage-two input (green curve) and stage-one input (red curve) are compared.

Subsequent measurements confirmed that the mirror radii in second stage were off by about 3 % from their optimum value. We believe this was the main limitation to the stacking enhancement in second stage. Fig. 7 shows the long-term stability, where the optical cavity phase noise were kept well below 50 mrad for 30 hours, resulting in a output stability of 1.5 %.

NEXT PLAN

Two 25X long cavities are being built, which will extend the stacking pulse number up to 125. And a new control platform based on Xilinx VC 707 and FMC 120 with four 16-bit fast ADC channels are being developed to support the 125 pulse stacking experiment. Preliminary result shows that the oscillator phase noise becomes more of a problem in 25x long cavities and we are developing a control scheme to reduce the oscillator phase noise.

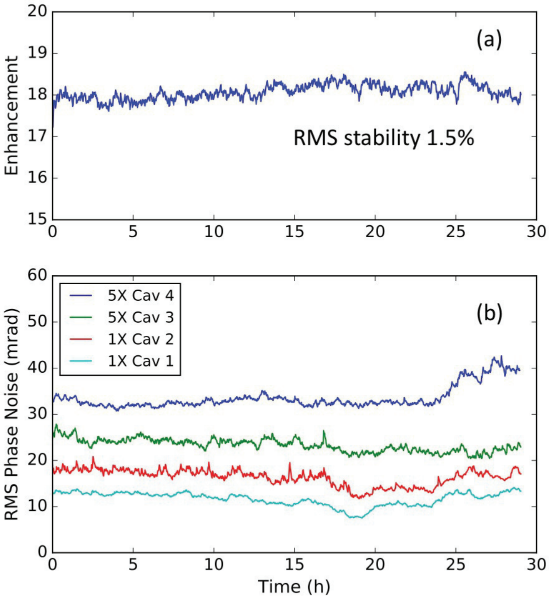

Figure 7: Long term stability measurements (a) Final pulse enhancement measurement (b) RMS phase noise of all optical cavities.

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