MULTICAVITY COHERENT PULSE STACKING USING HERRIOTT CELLS*

Y. Yang[†], R. Willcox, J. Byrd, L. Doolittle, Q. Du, G. Huang, Y. Xu
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Abstract

Coherent Pulse Stacking provides a promising way to generate a single high-intensity laser pulse by stacking a sequence of phase and amplitude modulated laser pulses using multiple optical cavities. Optical misalignment and phase stability are two critical issues that need to be addressed. Herriott cells are implemented for their relaxed alignment tolerance and a phase stabilization method based on cavity output pattern matching has been developed. A single pulse with intensity enhancement factor over 7.4 has been generated by stacking 13 modulated pules through a four-cavity stacking system. This can be a possible path for generating TW KHz laser pulses for a future laser-driven plasma accelerator.

INTRODUCTION

Laser-driven wakefield acceleration has become an emerging concept for a future accelerator facility, which could offer a far-more compact and cost-efficient approach compared with conventional accelerators [1]. However, one of the issues for developing a laser-based accelerator that has practical application is that the driving laser requirement is beyond current technology capability, particularly in terms of repetition rate. The state-of-the-art Joule-level sub-ps or fs laser amplifier can only operate at several hertz. Generation of 1 J to over 10 J laser at a repetition rate of kHz to 10 kHz, can bring laser-based acceleration from a lab-based concept into a facility which can benefit users.

Fiber-based amplifiers have seen significant increase in both average power and efficiency in recent years. However, the peak intensity is limited by optical damage or nonlinear effects. To overcome these limits, spatial and temporal coherent combination offers a possible solution [2]. A research collaboration among University of Michgan, LBNL and LLNL has been formed to explore the possibility of generating both high average power and high peak intensity laser systems based on fiber.

This paper focuses on a recently-proposed temporal combination scheme, called Coherent Pulse Stacking (CPS), which makes use of passive optical cavities to coherently stack a sequence of amplitude and phase modulated pulses into one high-intensity laser pulse [3]. Misalignment tolerance and phase stability are two challenges for CPS. We consider using Herriott cells to relax misalignment tolerance and fast photodiodes to detect the cavity phases for active feedback control. A four-cavity stacking system with FPGA-based control platform has been established [4]. An intensity enhancement factor of 7.4 has been achieved with a 13-pulse input. This could be a promising technique for generating high-intensity laser pulses based on fiber amplifiers.

MULTICAVITY STACKING CONCEPT AND SETUP

The optical cavity used for Coherent Pulse Stacking is shown in Fig. 1. It is an interferometer with a low-reflectivity input/output mirror, and a cavity length equal to the pulse repetition period. The preceding pulses can interfere with following pulses at the low-reflectivity mirror. The phase delay in the optical resonator will determine whether the interference is constructive or destructive. Constructive interference will cause the input pulse to remain in the cavity, while destructive interference will make the stored pulse exit the cavity. As is also shown in Fig. 1, when a sequence of equal-amplitude pulses enters the cavity, the corresponding output pulse amplitude will be either enhanced or reduced due to interference. With the amplitudes and phases of input pulses appropriately modulated, one can find certain cavity phases at which all the input pulses before the last one will remain in the cavities, and the last pulse can extract all the stored energy out of the cavities, thus being amplified to a considerable extent. A detailed theoretical description can be found in Ref. [3]. The highest intensity enhancement through a single cavity is 2.6. A sequence of cavities can stack more input pulses and extract more energy. This paper focuses on the four-cavity case, where numerical calculation shows an intensity enhancement around 7.8 can be achieved with a input of 13 modulated pulses.

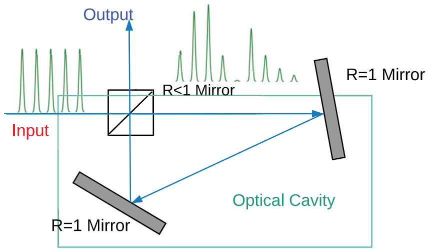

Figure 1: The optical cavity schematic used for Coherent Pulse Stacking.

The schematic of our four-cavity CPS experiment is shown in Fig. 2. A burst of 13 pulses are amplitude and phase modulated before entering the four-cavity stacking system. At certain phase delays of the four cavities (Φ_1, Φ_2, Φ_3, Φ_4),

---

[*] Work supported by Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231

[†] yaweiyang@lbl.gov

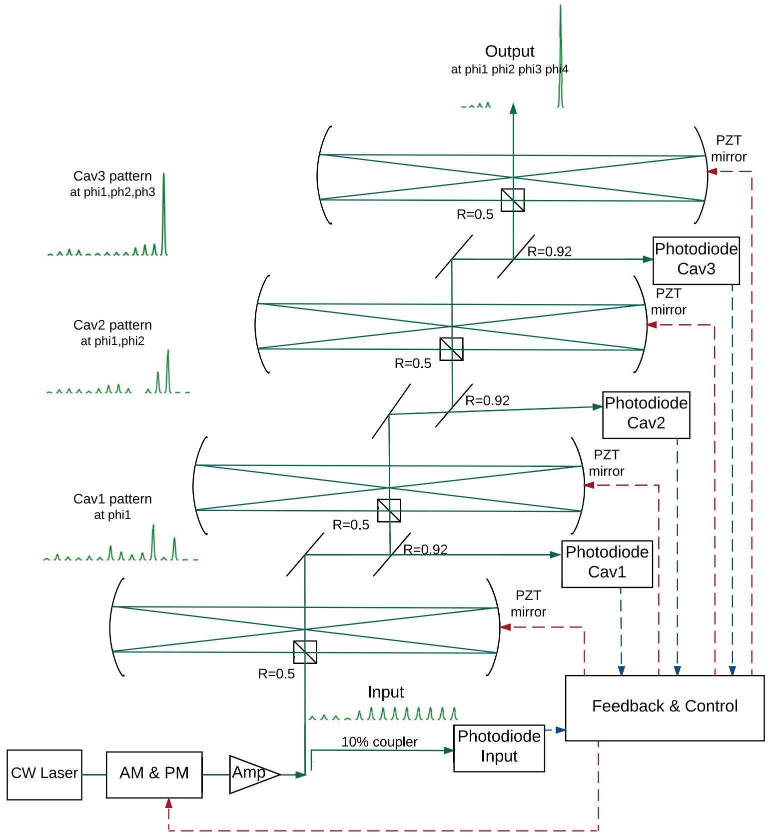

Figure 2: Experimental four-cavity CPS schematic. The input are 13 pulses, which are modulated by an amplitude modulator (AM) and a phase modulator (PM) with prescribed theoretical modulation. At certain cavity phases, one of the output pulses will be amplified while most of the other pulses will vanish. Green lines indicate the light paths, the dashed lines show the feedback and control paths, the feedback signals are detected by the photodiodes (dashed blue lines). The cavity lengths are controlled through the piezo transformer (PZT) mirror (dashed red lines).

these 13 pulses are stacked cavity after cavity, and eventually combined into one amplified output pulse.

Cavity Setup

CPS requires the spatial profiles of the following pulses to perfectly overlap with the preceding pulses stored in the cavities. Profile mismatch can be a major challenge. We use Herriott cells as the optical resonators, which turns out to be an excellent solution for this issue. A Herriott cell consists of two concave mirrors, placed on the same optical axis facing each other. It can be shown that at certain distance between the mirrors and with certain concave radius, the beam will return to the same path as it entered the cavity, with the same q parameter, thus the profile overlapping can be guaranteed [5]. Experiments have demonstrated that this cell has remarkable opto-mechanical stability. As is shown in Fig. 2, our experiment has implemented the simplest Herriott cells, which have the same radius R for the two mirrors and a mirror separation D = R. There is a cube beam-splitter in each cavity. The laser pulses entering the cavity through the cube will get reflected twice on each mirror and reach the interferometer following the same path as they entered, where they will interfere with the following pulses.

Phase Characterization and Control

The round-trip phases of all four cavities in our experiment need to be controlled and stabilized. Numerical simulation shows that the cavity phase errors should be controlled within two degrees, which corresponds to several nanometers in cavity length. This is a more problematic challenge.

University of Michigan uses the final stacked pulse output to feedback and control multiple cavities [6, 7]. In their method, each cavity phase is modulated and controlled using a stochastic parallel gradient descent (SPGD) algorithm, which effectively maximizes the stacking efficiency and maintains good stability over the long term. However, this scheme has a limited stability range, for such phase detection only works in a very narrow range around the operating point.

A full-range phase detection scheme is investigated. This scheme uses the relative intensities of the output pulses detected by a fast photodiode to characterize a cavity phase.

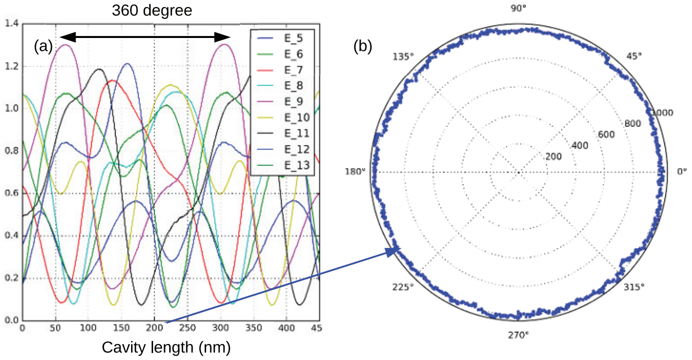

Figure 3: (a) Output intensity E_n vs cavity length (nm) (b) Phase can be derived by matching the amplitude vector to a unit circle in polar coordinates $e^{j\phi} = \vec{a} \cdot \vec{v}$.

Figure 3(a) gives an experimental result of different cavity output pulse amplitudes E_n vs a cavity length. It is apparent that single amplitude intensity E_n is not enough to determine the cavity phase, but if we write all the relative intensities as a vector $\vec{a}$=(E_1,E_2,...,E_N), this can be an excellent phase indicator. The easiest way to implement this is to use a lookup table, which can transfer the vector to the corresponding phase. And a computationally more elegant way is to find a fitting vector $\vec{v}$, which can transfer the amplitude vector $\vec{a}$ to a spot on a unit circle in polar coordinates by dot product $e^{j\phi} = \vec{a} \cdot \vec{v}$, as shown in Fig. 3(b). Using this technique, one could detect the phase of each cavity and make them phase-locked. The rms phase error of each cavity can be controlled within several degrees.

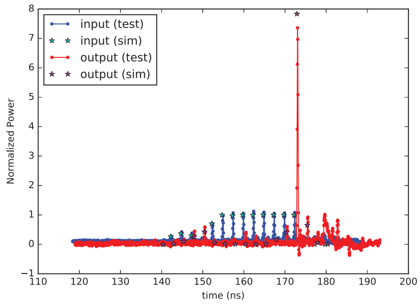

Figure 4: Four-cavity stacking result. The input pulses (blue line) and output pulses (red line) are compared. Theoretical predictions are marked on the curve.

EXPERIMENT RESULT

Four-cavity Coherent Pulse Stacking has been successfully demonstrated in our experiment. The mode-locked laser operates at 1064 nm central wavelength at 400 MHz. The pulse length is about 10 ps. The pulse modulations are performed in fiber-coupled electro-optic (EO) lithium niobate ($LiNbO_3$) modulators. A control platform has been developed [4], which is composed of a FPGA data acquisition system and a PC. The PC communicate with the FPGA system to acquire cavity phase data while control algorithms are implemented on the PC to implement active adjustment for the system.

Using the current configuration, an intensity enhancement of 7.4 has been achieved as shown in Fig. 4, which is only 5 % below numerical calculation. Further improvement in achieving higher stacking factor is expected after optimized beam-splitter cubes are installed. And new control algorithm design and optimization are ongoing to further improve stability and flexibility. The optimized control algorithm will be eventually fully implemented on the FPGA.

ACKOWLEDGEMENT

The authors are particularly grateful to John Ruppe and Prof. Almantas Galvanauskas from University of Michigan for helpful discussions.

REFERENCES

[1] W. Leemans and E. Esarey, "Laser-driven plasma-wave electron accelerators," *Phys. Today*, vol. 62, no. 3, pp. 44-49, 2009.

[2] S. Sven *et al.*, "A concept for multiterawatt fibre lasers based on coherent pulse stacking in passive cavities," *Light: Science & Applications*, vol. 3, no. 10, p. e211, 2014.

[3] T. Zhou *et al.*, "Coherent pulse stacking amplification using low-finesse Gires-Tournois interferometers," *Optics Express*, vol. 23, pp. 7442-7462, 2015.

[4] Y. Xu *et al.,* "FPGA Control of Laser Pulse Stacking," presented at NA-PAC'16, Chicago, IL, USA, paper TUPOA41, this conference.

[5] D. Herriott, H. Kogelnik, and R. Kompfner. "Off-axis paths in spherical mirror interferometers," *Applied Optics*, vol. 3, pp. 523-526, 1964

[6] J. Ruppe *et al.*, "Cascading of Coherent Pulse Stacking Using Multiple Gires-Tournois Interferometers," *Advanced Solid State Lasers* 2015, pp. AW3A.4.

[7] J. Ruppe *et al.*, "Coherent Pulse Stacking Extension of CPA to 9ns Effectively-Long Stretched Pulse Duration," Conference on Lasers and Electro-Optics 2016, pp. SM4I.2.