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# OPTICAL PHASE LOCKING OF MODELOCKED LASERS FOR PARTICLE ACCELERATORS*

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### *Abstract*

Particle accelerators require precise phase control of the electric field through the entire accelerator structure. Thus a future laser driven particle accelerator will require optical synchronism between the high-peak power laser sources that power the accelerator. The precise laser architecture for a laser driven particle accelerator is not determined yet, however it is clear that the ability to phase-lock independent modelocked oscillators will be of crucial importance. We report the present status on our work to demonstrate long term phaselocking between two modelocked lasers to within one dregee of optical phase and describe the optical synchronization techniques that we employ.

## INTRODUCTION

Laser-driven acceleration of relativistic particles in vacuum has been proposed and studied on a theoretical basis for many years [1,2,3]. A strong motivation for this effort has been the potential ~ 1 GeV/m sustained energy gradient that laser-driven particle accelerators could deliver [4]. Two elements that have allowed this particle acceleration technology to become feasible are the appearance of tabletop high peak power lasers [5] and the maturing of micro fabrication technologies [6]. Furthermore, the physics principle for laser-driven acceleration of relativistic electrons in a structure loaded vacuum was recently demonstrated [7]. At present extensive research and development is being carried out on the architecture design of extended laser accelerator structures [8,9] and on efficiency and luminosity considerations [10,11]. On the other hand little thought has been devoted on the still pending development of the laser architecture that will drive an extended laser driven particle accelerator. While it is true that laser-driven particle acceleration profits from progress made in laser power scaling, wallplug efficiency improvements [12], newly developed laser frequency comb stabilization and pulse synchronization techniques [13] there are still laser requirements specific to particle acceleration that will require dedicated research. One such aspect is the ability to sustain optical stability between independent modelocked oscillators to within 1 degree of phase for an extended period of time.

The individual laser stabilization techniques required to reach our objective already exist, and our task is to combine and adapt them to reach our goal of long term optical phase coherence between modelocked lasers.

## DISCUSSION

### *Laser Frequency Stabilization Methods*

Single mode continuous wave (CW) lasers require one parameter (the length of the laser cavity) to control the frequency of the laser beam. The frequency $\nu_n$ is inversely proportional to the optical path length of the laser cavity $l$ and is given by

$$\nu_n = n\frac{c}{2l} \equiv nf_{rep} \qquad 1$$

$f_{rep}$ is the frequency spacing *c* is the speed of light and *n* is a large integer representing the mode number. For a typical 1 m cavity and a 1 µm wavelength *n*~106. Small perturbations in $l$ can be used for active frequency stabilization [14] and for control of the optical phase of the laser beam.

A typical modelocked laser possesses on the order of 104 simultaneous modes $\nu_n$. Since intra-cavity dispersion affects the effective cavity length that each mode observes a modelocked laser requires two parameters to control its pulse structure. The cavity length of the laser controls the pulse envelope repetition rate $f_{rep}$, and the dispersion in the cavity controls the carrier-to-envelope optical phase relationship. In the frequency domain the dispersion causes the modes to shift by a uniform frequency comb offset $\delta$ [15]

$$\nu_n = n\frac{c}{2l} + \delta \qquad 2$$

The consequence of the comb offset on the carrier-to-envelope relationship is a pulse-to-pulse phase slip $\Delta\phi$

$$2\pi\delta = \Delta\phi \cdot f_{rep} \qquad 3$$

Thus, in order to phase lock two separate modelocked lasers the pulse repetition rate $f_{rep}$ and the comb offset $\delta$ of the two lasers have to be matched. Comb offset detection and control techniques [16,17,18] as well as techniques for sub-femtosecond pulse stabilization [19]

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have been developed and reported extensively in recent years.

## The Proposed Experimental Approach

Present frequency comb and pulse envelope stabilization techniques alone are not going to be sufficient to lock the optical phase of two modelocked lasers to within 1degree of optical phase. While balanced cross-correlation techniques can detect pulse envelope timing to within ~1/10 of an optical cycle an additional higher resolution timing monitor is required to detect optical phase shifts to within 1 degree. This can be accomplished by a simple interferometric detection scheme that generates a optical phase dependent error signal that actuates on a variable optical delay for one laser beam. Figure 1 is a schematic of the proposed two-laser optical phase locking scheme.

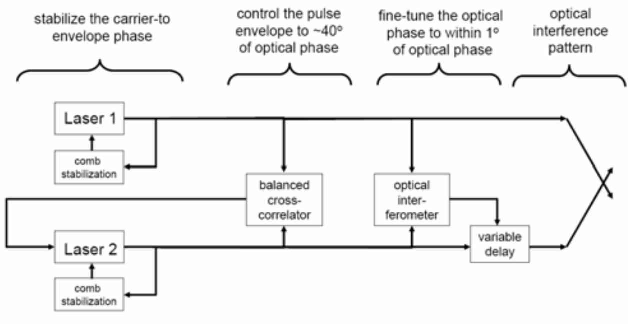

Figure 1

Each modelocked laser has its comb offset stabilized to the same reference frequency offset $\delta$, which does not have to be zero but has to be the same for both lasers. Laser 1 is the master laser and can be RF-locked to an external reference $f_{rep}$. A balanced crosscorrelator measures the timing difference of the pulse envelopes between laser 1 and laser 2 and produces an error signal that adjusts the cavity length of laser 2. An optical interferometer placed downstream detects optical phase drifts between laser beams 1 and 2 and produces an error signal that controls a PZT driven variable delay arm for laser beam 2. Optical phase stability of one degree of optical phase will manifest as a stable fringe pattern observable by a CCD between lasers beams 1 and 2 that is stable to 1/360th of a fringe.

## Comb Offset Detection and Control

Initial comb offset detection and control experiments were carried out with a commercial 80 MHz, 1 W, 800 nm, 100 fsec pulse Ti:Sapphire laser. To broaden the frequency comb width of the laser beam to a full octave a white light continuum fiber was used. To detect the comb offset the standard self-referencing technique was employed [20]. A PMT followed by bandpass filters was employed to isolate the comb offset frequency beat signal which was converted by a frequency-to-voltage converter to an error signal. Figure 2 shows the electronics employed to extract the comb offset frequency.

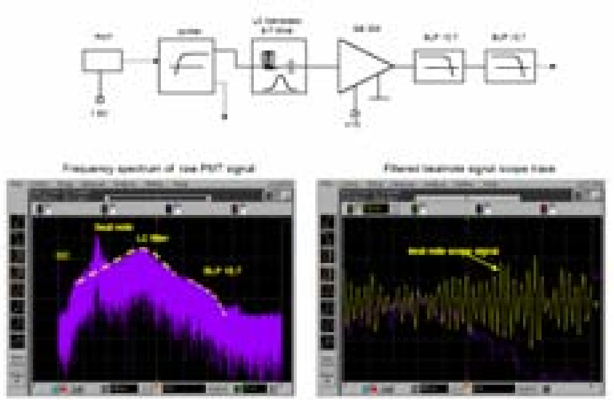

Figure 2

The laser intra-cavity dispersion can be adjusted by control of dispersion compensating prisms in the cavity or more simply by small adjustments in the power of the pump laser beam. For convenience the latter method was employed. An acousto-optic modulator placed in the pump laser beam allowed for electronic control the intra-cavity dispersion of the modelocked laser. Figure 3 shows the comb offset error signal when a 1 kHz square wave and a 10 kHz triangle wave are applied through the AOM to the laser dispersion.

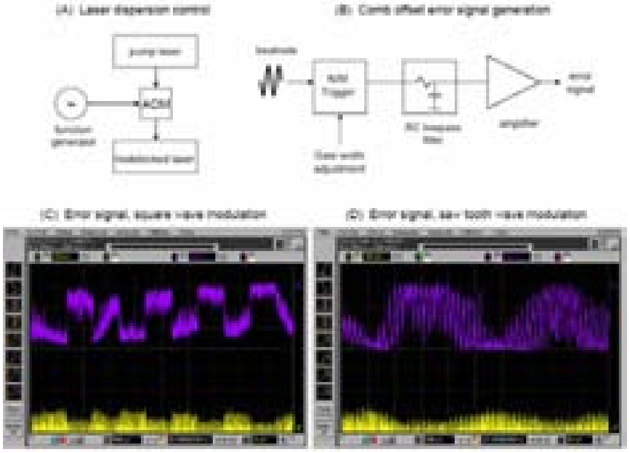

Figure 3

## Pulse Envelope Timing Monitor

A balanced crosscorrelator as described by Schible et al [19] was constructed. In essence a balanced crosscorrelator consists of two separate crosscorrelators with optical path lengths set such that the crosscorrelators give an optimum crosscorrelation signal at slightly different relative beam timings. The difference of the two signals gives a very steep error signal curve that allows for the sought sub-fsec timing resolution. To test the sensitivity of the device the laser beam from the modelocked laser was split into a beam going through a fixed delay and another beam going through a PZT controlled delay arm. The two beams were sent into the balanced crosscorrelator whose sensitivity was tested as a function of delay changes caused by the PZT. Figure 4 illustrates the layout and the resulting error signal observed from a 240 attosecond delay.

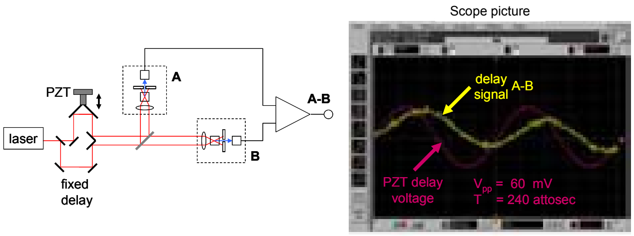

Figure 4

## FUTURE WORK

We have successfully tested the individual techniques for phase locking with a single commercial modelocked Ti:Sapphire laser. For the next phase of experiments we are switching to a home built Yb:glass modelocked fiber laser that is more suitable for particle acceleration. We are presently setting up the comb offset detection apparatus and are preparing to build a second fiber modelocked laser that will allow us to carry out the phase locking experiment for modelocked lasers. Furthermore we plan to develop and characterize amplifiers for modelocked lasers.

Although aimed for optical phase locking, these experiments provide an opportunity to test other important aspects such as reliability, wallplug efficiency and compactness that will ultimately help determine the future laser architecture for an extended laser driven particle accelerator.

## REFERENCES

[1] Y.W. Chan, “Ultra-Intense Laser Radiation as a Possible Energy Booster for Relativistic Charged Particle”, Phys. Lett. Vol. 35, No. 4 p. 305-306 (1971)

[2] R.H. Pantell, M.A. Piestrup, “Free-electron momentum modulation by means of limited interaction length with light”, Applied Physics Letters, 32, no. 11, p 781-783 (1978)

[3] E. Esarey, P. Sprangle, J. Krall, Laser Acceleration of Electrons in Vacuum, Physical Review E, 52, p 5443-5453 (1995)

[4] Y.C. Huang, D. Zheng, W.M. Tulloch, R.L. Byer, “Proposed structure for a crossed-laser beam GeV per meter gradient vacuum electron linear accelerator”, Applied Physics Letters, 68, no. 6, p 753-755 (1996)

[5] J. Limpert, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, R. Iliew, F. Lederer, J. Broeng, G. Vienne, A. Petersson, C. Jakobsen, “High-power air-clad large-mode-area photonic crystal fiber laser”, Optics Express, Optics Express, Vol. 11, No. 7, p. 818-823 (2003)

[6] see structures paper submitted to PAC05

[7] T. Plettner et al, “Accelerating Relativistic Electrons with Visible Light”, submitted to Phys. Rev. Lett. (2005)

[8] X. Eddie Lin, Photonic band gap fiber accelerator, Phys. Rev. ST Accel. Beams 4 051301 (2001)

[9] B. M. Cowan, Two-dimensional photonic crystal accelerator structures, Phys. Rev. ST Accel. Beams 6 101301 (2003)

[10] R.H. Siemann, “Energy efficiency of laser driven, structure based accelerators”, Phys. Rev. ST AB. 7 061303 (2004)

[11] Y. C. Neil Na, R. H. Siemann, R.L. Byer, “Energy efficiency of an intracavity coupled, laser-driven linear accelerator pumped by an external laser”, Phys. Rev. ST. AB. 8, 031301 (2005)

[12] N. A.Pikhtin, S. O.Slipchenko, D.A.Vinokurov, M. A.Khomylev, I. S.Tarasov, “72% wallplug efficiency and 16W CW front facet output optical power from 100-μm-aperture laser diode”, ASSP 2005 conference proceedings (2005)

[13] R. K. Shelton, L-S. Ma, H. C. Kapteyn, M. M. Murnane, J. L. Hall, J. Ye “Phase-Coherent Optical Pulse Synthesis from Separate Femtosecond Lasers”, Science Vol. 293, p.286-1289 (2001)

[14] T. Day, E.K. Gustafson, R.L. Byer, “Active frequency stabilization of a 1.062 μm, Nd:GGG diode-laser-pumped nonplanar ring oscillator to less than 3 Hz of relative linewidth”, Opt. Lett. Vol. 15, No. 4, p. 221-223 (1989)

[15] D.Jones, S.Diddams, J.Ranka, A.Stentz, R.Windeler, J.Hall, S.Cundiff, “Carrier-Envelope Phase Control of Femtosecond Mode-Locked Lasers and Direct Optical Frequency Synthesis”, Science 288, 635 (2000)

[16] J.Reichert, M.Niering, R.Holzwarth, M.Weitz, Th.Udem, T.W.Hänsch, “Phase Coherent Vacuum-Ultraviolet to Radio Frequency Comparison with a Mode-Locked Laser” Physical Review Letters 84, 3232 (2000)

[17] T. M. Fortier, D. J. Jones, J. Ye, S. T. Cundiff, “Long-term carrier-envelope phase coherence”, Opt. Lett. Vol. 27, No. 16, p. 1436-1438 (2002)

[18] J.Rauschenberger, T.M. Fortier, D. J. Jones, J. Ye, S. T. Cundiff, “Control of the frequency comb from a modelocked Erbium-doped fiber laser”, Opt. Express, Vol. 10, No. 24 p. 1404-1410 (2002)

[19] T.R. Schibli, J. Kim, O. Kuzucu, J.T. Gopinath, S.N. Tandon, G.S. Petrich, L.A. Kolodziejski, J.G. Fujimoto, E.P. Ippen, F.X. Kaertner, “Attosecond active synchronization of passively mode-locked lasers by balanced cross correlation”, Opt. Lett., vol. 28, no. 11, p. 947-949 (2003)

[20] H..R. Telle G. Steinmeyer, A.E. Dunlop, J. Stenger, D.H. Sutter, U. Keller, “Carrier-envelope offset phase control:A novel concept for absolute optical frequency measurement and ultrashort pulse generation” , Appl. Phys. B 69, 327-332 (1999)