SECONDARY WAVELENGTH STABILIZATION OF UNBALANCED MICHELSON INTERFEROMETERS FOR THE GENERATION OF LOW-JITTER PULSE TRAINS

R. J. SHALLOO AND L. CORNER*

John Adams Institute for Accelerator Science, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK
**Corresponding author: laura.corner@physics.ox.ac.uk*

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We present a double unbalanced Michelson interferometer producing up to 4 output pulses from a single input pulse. The interferometer is stabilized with the Hänsch-Couillard method using an auxiliary low power continuous wave laser injected into the interferometer, allowing the stabilization of the temporal jitter of the output pulses to 0.02fs. Such stabilized pulse trains would be suitable for driving multi-pulse laser wakefield accelerators and the technique could be extended to include amplification in the arms of the interferometer. © 2016 Optical Society of America

OCIS codes: *OCIS Codes: (120.3180) Interferometry, (140.3425) Laser stabilization, (260.316) Interference, (320.5550) Pulses.*

http://dx.doi.org/10.1364/OL.99.099999

Controllable, flexible, high contrast laser pulse trains have numerous applications in many areas of science, including coherent control of molecular processes [1, 2, 3], as drive beams for photocathodes [4], for quasi-phasematched high harmonic generation [5], generation of THz pulse trains [6] or for efficiently driving laser plasma wakefield acceleration (multi-pulse laser wakefield acceleration or MP-LWFA) [7, 8]. Trains of this type can be created from a single laser pulse by many methods, for example spectral filtering using spatial light modulators or phase masks [9], and pulse splitting with single or stacked birefringent crystals [10], or multiple Michelson interferometers [11].

For many applications, the pulse train has to be very stable i.e. with low timing jitter between the pulses. This is important, for example, if the pulses in the train have to be separated by exactly the plasma period, as is the case for MP-LWFA, or used to create electron bunches from a photocathode that are precisely timed to the rf phase of an accelerator. Methods involving splitting and recombining beams to create pulse trains are susceptible to jitter (e.g. from mechanical fluctuations of the optics) and need to be stabilized to precisely control the timing between pulses. Interferometers can be stabilized with a variety of methods, including Pound-Drever-Hall [12] or Hänsch-Couillard (HC) [13] locking. For pulsed systems, locking requires the pulses from each arm of the interferometer to be temporally overlapped to provide an error signal for stabilization [14]; therefore, an interferometer designed to split one input pulse into a train cannot use these methods. In this paper we present a method for stabilizing unbalanced interferometers using a secondary, continuous wave (cw) laser and HC locking. Provided that the path length difference between the two arms of the interferometer is less than the coherence length of the cw laser, we show it is possible to stabilise the interferometer with the cw laser alone and that a single pulsed laser input can be used to generate a pulse train from the interferometer at the same time.

To test this idea a proof-of-principle experiment was designed. Pulse trains were created using two unbalanced Michelson interferometers, as shown in Figure 1. The first interferometer creates a pair of pulses, temporally separated by the optical path difference between the two arms divided by the speed of light, from a single input pulse. The second interferometer creates another pair of pulses from each input pulse, generating a train of four pulses in total.

The laser used to create the pulse train was an ytterbium (Yb) doped fibre amplifier (Fianium) producing pulses of 8 ps (FWHM) duration and approximately 2 nJ energy at a pulse repetition rate of 52 MHz. The locking laser was a 30 mW cw laser pointer (Roithner Lasertechnik) operating at 1064 nm. The locking and pulsed lasers were combined on a polarizing beam splitter (PBS) which was followed by a half-wave ($\lambda/2$) plate which rotated the polarization of both beams to 45° to the vertical axis. The combined laser beam was split into the two arms of a Michelson interferometer using a PBS. Each arm contained a quarter-wave ($\lambda/4$) plate to ensure all the light from each arm of the Michelson was sent to the output port. One of the mirrors in the Michelson was mounted on a piezoelectric actuator for the locking stabilization; the mirror was additionally mounted on a 25 mm range translation stage for gross control of the path length difference between the two arms. A small proportion of the total (cw and pulsed) output beam was reflected from a neutral density filter into a HC detector, comprising a $\lambda/4$ plate and a PBS with a photodiode at each output. When the path lengths of the two arms of the Michelson were different, the output of the interferometer consisted of two pulses, one vertically and one horizontally polarized, and the cw beam, which had a varying polarization state depending on the phase difference between its vertical and horizontal components. When the interferometer was correctly phase locked, the polarization of the cw beam was linear at 45 degrees to the horizontal. The $\lambda/4$ plate altered this to circular polarization, giving equal signals on the two photodiodes in the HC detector. Any drift in the path length difference between the two arms of the interferometer generated an elliptically polarized cw

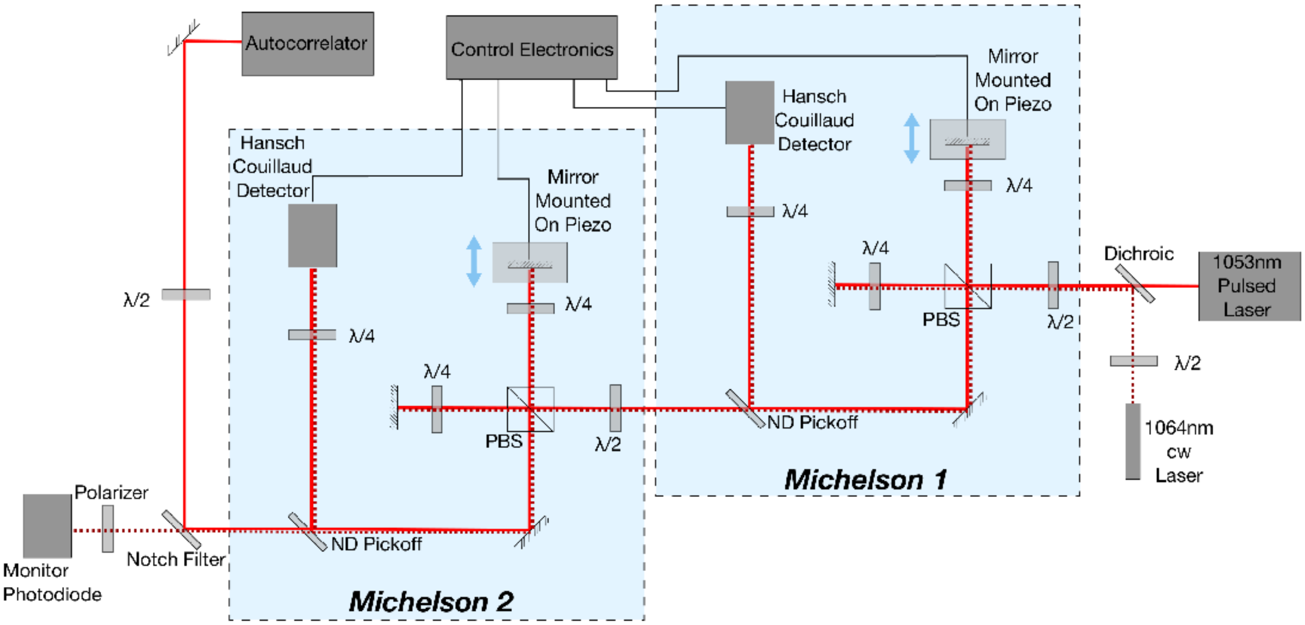

Figure 1 Experimental setup

beam, which produced unbalanced signals on the photodiodes. The output of the photodiodes was sent to the control electronics (TEM Messetechnik). The control box generated an error signal from the photodiode output which was fed back to the piezoelectric actuator on the mirror in the Michelson to stabilize the path length difference between the arms.

The majority of the output (cw and pulsed) beam from the first Michelson was directed into another identical Michelson interferometer, to create a train of four pulses as described above. As in the first interferometer, a small proportion of the combined output beam from the second interferometer was directed to a second HC detection system and channel of the control electronics box for stabilization of the second interferometer. The remaining output, consisting of the 1064 nm cw locking beam and the 1053nm pulse train, was separated by a 5 nm wide notch filter, which transmitted the 1064 nm cw beam through a 45° PBS onto a photodiode to monitor the stability of the interferometers with and without locking.

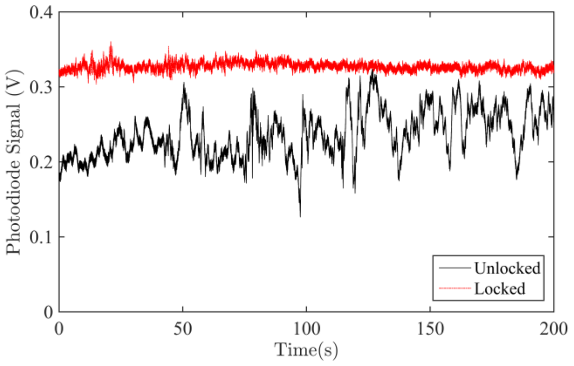

Figure 2 Time series data showing the monitor cw laser signal at the output of the experimental setup with both interferometers locked (dashed line) and unlocked (solid line).

The 1053 nm pulsed beam was reflected from the filter and directed into a commercial scanning long arm autocorrelator to measure the pulse trains produced by the interferometers. It should be noted that for completely independent control of the spacing between all four pulses it would be necessary for the two interferometers to be arranged in parallel and locked independently, with a stage to control the time delay between the two pairs of pulses. However, two interferometers in series were sufficient for this proof-of-principle demonstration.

Initially both interferometers were balanced to temporally overlap the pulses from the fibre laser and stabilized separately using the cw laser. Then both interferometers were deliberately unbalanced in path length to produce temporally separated output pulses. The first Michelson had an optical path length difference chosen to produce a separation between the two output pulses of 33 ps, and the second Michelson had a path length difference to give 67 ps pulse separation. This produced a total output train of four pulses individually separated by 33 ps. The two Michelsons were then both locked using the cw laser signal. This was achieved by locking the first Michelson to produce a stable input to the second, which was then locked in turn. The ND filters used to reflect a small amount of the cw laser into the HC detector also reflected the pulsed laser which had a higher peak power than the cw laser. However, this did not affect the lock as when the pulses were temporally separated there was one horizontally and one vertically polarized pulse incident on the detector that did not interfere with each other. These pulses produced a constant voltage on each photodiode in the HC detector which could be accounted for by adjusting the DC offset in the control electronics without affecting the generation of the error signal from the cw laser.

Figure 2 shows time series data of the cw laser transmitted through the two stacked interferometers and analyser PBS, monitored on the photodiode with the two interferometers unbalanced (i.e. with none of the pulses temporally overlapped), when both unlocked and locked, respectively, demonstrating that

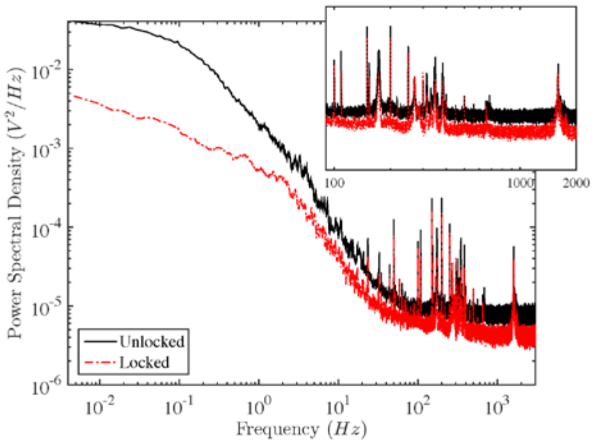

Figure 3 Power spectral density of the cw monitoring signal shown in Figure 2 with both interferometers locked (dashed line) and unlocked (solid line).

the feedback locking system successfully stabilised the polarisation state of the cw locking beam and hence the path length differences between the arms of the two interferometers.

Figure 3 shows the power spectral density of the time series data i.e. the frequency noise of the interferometers, where the inset shows the region between 100 and 1000 Hz in more detail. It clear that the locking strongly improves the stability of both interferometers below 100 Hz, but closer examination of the region above 100 Hz shows that it also reduces or removes frequency noise up to 1 kHz. The performance of the cw laser lock was independent of whether the pulsed laser was on or off.

The output of the unbalanced interferometers is shown in Figure 4 which shows the autocorrelation of the pulse train reflected from the notch filter, together with the calculated autocorrelation and pulse train (inset), determined from the known laser pulse duration and path length difference between the arms of the two interferometers. Seven peaks are clearly shown in the autocorrelation, confirming that a train of four pulses has been successfully generated (one pulse in the autocorrelation is slightly clipped owing to the limited temporal scan of the autocorrelator).

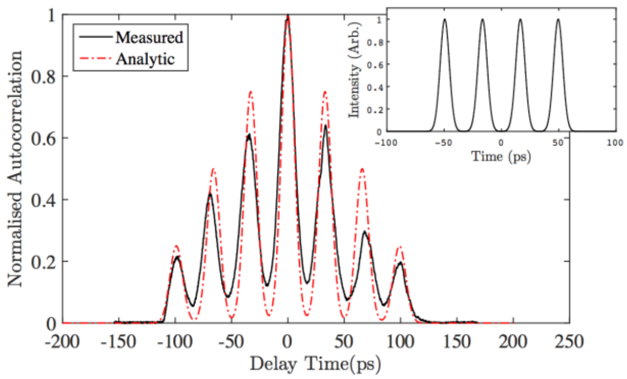

Figure 4 Measured autocorrelation of the pulse train generated from the two locked interferometers (solid line), with the simulated autocorrelation (dashed line). The pulse train calculated from the known pulse duration and path length separation of the interferometers, used to simulate the expected autocorrelation, is shown in the inset.

The stability of the locked interferometers is calculated from the time series data to be λ/180 rms, which corresponds to a temporal jitter between the output pulses of 0.02 fs, or 6×10^{-7} of the pulse spacing. This is well below the jitter between pulses in a train required to successfully drive a wakefield [8].

It would be possible to generate higher pulse energy output by including fibre amplifiers in each arm of the two Michelsons, and this is the subject of further investigation. Longer (2n) pulse trains can be easily generated by extending this experiment to n interferometers and the amplitude of each pulse can be controlled individually by adjusting the λ/2 plates before each interferometer, allowing full flexibility over both the energy and spacing of each pulse in the train.

In summary, we have demonstrated the stabilization of two unbalanced Michelson interferometers with a low power cw laser and used this arrangement to generate flexible pulse trains from a higher power pulsed laser. The stability of the pulse train is excellent and exceeds that required to use such a train to drive a laser plasma wakefield accelerator.

Funding: UK Science and Technology Facilities Council (STFC UK) (ST/J002011/1); Helmholtz Association of German Research Centres (VH-VI-503).

---

1. A.M. Weiner, D.E. Leard, Gary P. Wiederrecht and Keith. A. Nelson, Science 247, 1317 (1990).
2. James P. Cryan, Philip H. Bucksbaum and Ryan N. Coffee, Phys. Rev. A, 80, 063412 (2009).
3. W.S. Warren and Ahmed H. Zewail, J. Chem. Phys. 78, 2279 (1983).
4. A. Aryshev, M. Shevelev, Y. Honda, N. Terunuma and J. Urakawa, arXiv:1507.03302 [physics.acc-ph]
5. Kevin O'Keeffe, Daivd T. Lloyd and Simon M. Hooker, Opt. Exp. 22, 7722 (2014)
6. C.W. Siders, J.L.W. Siders, A.J. Taylor, S.-G. Park, M.R. Melloch and A.M. Weiner, Opt. Letts. 24, 241 (1999)
7. D. Umstadter, J. Kim, E. Esarey, E. Dodd and T. Neubert, Phys. Rev. E, 51, 3484 (1995)
8. S.M. Hooker, R. Bartolini, S.P.D. Mangles, A. Tünnermann, L. Corner, J. Limpert, A. Seryi and R. Walczak, J. Phys. B: At. Mol. Opt. Phys. 47, 234003 (2014).
9. A.M. Wiener, Rev. Sci. Insts. 71, 1929 (2000).
10. Shian Zhou, Dimitre Ouzounov, Heng Li, Ivan Bazarov, Bruce Dunham, Charles Sinclair and Frank W. Wise, Appl. Opt. 46, 8488 (2007).
11. C.W. Siders, J.L. W. Siders, A.J. Taylor, S. Park and A.M. Weiner, Appl. Opt. 37, 5302 (1998).
12. R.W.P. Drever, J.L. Hall, F.V. Kowalski, J. Hough, G.M. Ford, A.J. Munley and H. Ward, Appl. Phys. B. 31, 97 (1983).
13. T.W. Hänsch and B. Couillard, Opt. Communs. 35, 441 (1980).
14. Radoslaw Uberna, Andrew Bratcher and Bruce G. Tiemann, IEEE Quantum Electron. 46, 1191 (2010).

---

1. A.M. Weiner, D.E. Leard, Gary P. Wiederrecht and Keith. A. Nelson, ‘Femtosecond Pulse Sequences Used for Optical Manipulation of Molecular Motion’, Science 247, 1317 (1990).
2. James P. Cryan, Philip H. Bucksbaum and Ryan N. Coffee, ‘Field-free alignment in repetitively kicked nitrogen gas’, Phys. Rev. A, 80, 063412 (2009).
3. W.S. Warren and Ahmed H. Zewail, ‘Multiple phase-coherent laser pulses in optical spectroscopy. I. The techniques and experimental applications’, J. Chem. Phys. 78, 2279 (1983).
4. A. Aryshev, M. Shevelev, Y. Honda, N. Terunuma and J. Urakawa, ‘Femtosecond response time measurements of a Cs2Te photocathode’, arXiv:1507.03302 [physics.acc-ph]
5. Kevin O’Keeffe, Daivd T. Lloyd and Simon M. Hooker, ‘Quasi-phase-matched high order harmonic generation using tunable pulse trains’, Opt. Exp. 22, 7722 (2014)
6. C.W. Siders, J.L.W. Siders, A.J. Taylor, S.-G. Park, M.R. Melloch and A.M. Weiner, ‘Generation and characterization of terahertz pulse trains from biased, large-aperture photoconductors’, Opt. Letts. 24, 241 (1999)
7. D. Umstadter, J. Kim, E. Esarey, E. Dodd and T. Neubert, ‘Resonantly laser-driven plasma waves for electron acceleration’, Phys. Rev. E, 51, 3484 (1995)
8. S.M. Hooker, R. Bartolini, S.P.D. Mangles, A. Tünnermann, L. Corner, J. Limpert, A. Seryi and R. Walczak, ‘Multi-pulse laser wakefield acceleration: a new route to efficient, high-repetition-rate plasma accelerators and high flux radiation sources’, J. Phys. B: At. Mol. Opt. Phys. 47, 234003 (2014).
9. A.M. Wiener, ‘Femtosecond pulse shaping using spatial light modulators’, Rev. Sci. Insts. 71, 1929 (2000).
10. Shian Zhou, Dimitre Ouzounov, Heng Li, Ivan Bazarov, Bruce Dunham, Charles Sinclair and Frank W. Wise, ‘Efficient temporal shaping of ltrashort pulses with birefringent crystals’, Appl. Opt. 46, 8488 (2007).
11. C.W. Siders, J.L. W. Siders, A.J. Taylor, S. Park and A.M. Weiner, ‘Efficient high-energy pulse-train generation using a 2n-pulse Michelson interferometer’, Appl. Opt. 37, 5302 (1998).
12. R.W.P. Drever, J.L. Hall, F.V. Kowalski, J. Hough, G.M. Ford, A.J. Munley and H. Ward, ‘Laser Phase and Frequency Stabilization Using an Optical Resonator’, Appl. Phys. B. 31, 97 (1983).
13. T.W. Hänsch and B. Couillard, ‘Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity’, Opt. Communs. 35, 441 (1980).
14. Radoslaw Uberna, Andrew Bratcher and Bruce G. Tiemann, ‘Coherent Polarization Beam Combination’, IEEE Quantum Electron. 46, 1191 (2010).