A femtosecond-precision, fiber-optic timing transfer system with long-term stable, polarization maintaining output

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Abstract

A fiber-based, all-optical system for femtosecond-precision, long-term, timing transfer and synchronization of microwave electronics and lasers at the kilometer scale is presented. This approach enables the implementation of femtosecond pulse, X-ray free-electron lasers, owing to the high-precision and robust operation. The system incorporates a fiber polarization controller for long-term synchronization of remote lasers, and operates with an optical timing detector based on balanced optical cross-correlation. We demonstrate continuous, unaided timing distribution over 168-hours with 5 fs rms precision. Also, the first demonstration of timing transfer from local to remote ultrafast, fiber laser with an all-optical, ultrafast technique is shown for over 5 hours with 4 fs rms transfer precision. This represents timing transfer over 340 m of fiber with an unprecedented fractional relative timing stability of 10^{-19}. A study of linear and non-linear effects impacting performance is presented, along with design guidelines, while it is shown that minimization of polarization mode dispersion and non-linearity are critical design considerations for optimal performance.

1. Introduction

Ultrafast fiber-optic lasers hold tremendous promise as a practical instrument for synchronizing remote optical and microwave electronic devices via fiber-optic links. Since such lasers simultaneously capture the benefits of exceptionally low-noise optical performance, while pulsing at microwave-frequency repetition rates, it is possible to achieve femtosecond-level timing stability while providing a useful output signal in the microwave band, and at any harmonic of the repetition rate[1]. Therefore, ultrafast timing synchronization over optical fiber is being developed for X-ray free-electron laser facilities requiring femtosecond synchronization over a distance of 300 to 3000 m. Also, the technique holds promise for higher-frequency, microwave telescope arrays which require many independent dishes to remain interferometrically synchronized over many kilometers, in extremes of weather and temperature, for long periods of time. The ultrafast laser is unique in that it combines the convenience of a microwave signal source with the low-noise performance of an optical oscillator [2].

2. System Design

The heart of the system is the optical pulse envelope timing detector, known as the balanced optical cross-correlator (BOC). The BOC performs an optical cross-correlation between the pulse returning from the link and a newly emitted pulse from the laser. In this way, an amplitude insensitive signal proportional to the time between the pulse envelopes can be extracted [3]. The fundamental assumption of timing distribution is that the time taken for the signal to reach the remote location (one-way delay) is related to the round-trip propagation delay in a know way. If so, it is possible to measure the round-trip delay, and make corresponding adjustments to the one-way delay to keep the remote clock signal uncorrupted by fluctuations in the transmission line. This basic scheme is described in
FIG. 1. The master laser, which may be loosely synchronized to a microwave frequency standard, is an additive pulse mode-locked erbium fiber soliton laser, emitting at 1550 nm with a pulse repetition rate of 200 MHz[4]. A faraday rotating mirror (FRM) is added at the end of the link so that polarization of backward propagating pulses is preserved. After measurement of the timing error from the in-loop BOC, the corrective delay is applied to the link through a combination high-resolution stepper motor and 40 µm travel piezoelectric stack by the locking electronics.

The fiber link consists of 300 meters of Corning SMF-28e fiber, spliced to approximately 40 meters of Avanex dispersion compensating fiber (DCF) which compensates for both dispersion and dispersion slope of the SMF-28e. For links longer than 100 m, dispersion slope, or third order dispersion (TOD), becomes significant. Moreover, as is shown, DCF has the added benefit of eliminating net TOD, which decreases amplitude to timing conversion in the link.

In addition, it is necessary to incorporate an erbium doped fiber amplifier (EDFA) within the fiber link to bi-directionally amplify circulating pulses. A system will have a total typical single-pass loss of 8 dB, or a round-trip loss

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of 12 dB. Finally, at the end of the link, we place an electronic polarization controller (Thorlabs DPC5500) to polarize the output before a ~1 m section of PM fiber, which couples to the FRM.

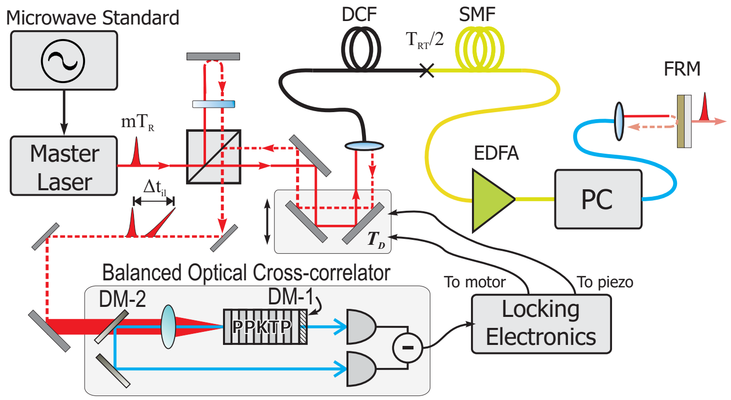

FIG. 1. Layout of an ultrafast timing link with PM output, based on a balanced optical-cross-correlator. SMF; single mode fiber. PC; polarization controller. DM-1; dichroic mirror (T: 1550, R: 775 nm). DM-2; (T: 775, R: 1550 nm).

3. Experimental Results

We demonstrate long-term timing transfer from the master laser to a remote laser through the fiber link, entirely by optical means. To characterize the performance of the timing link system by itself, we stabilized a 300 m SMF-28e fiber link with 40 m of DCF, in the laboratory. The PM output of the link was then combined with a portion of the free space output of the master laser, and sent into a second BOC, as shown in FIG. 2(a). The results, as shown in FIG. 3(a), demonstrate 5 fs rms drift over 168 hours, while the system corrected for 25 ps peak-to-peak fluctuations in the fiber. Such long term operation is possible due to the polarization controller. The vast majority of the residual drift is from slow fluctuations correlated to the daily temperature fluctuations of the laboratory. Moreover, the residual out-of-loop, high-frequency jitter is only 1 fs rms [0.1 Hz, 100 kHz] [1]**.**

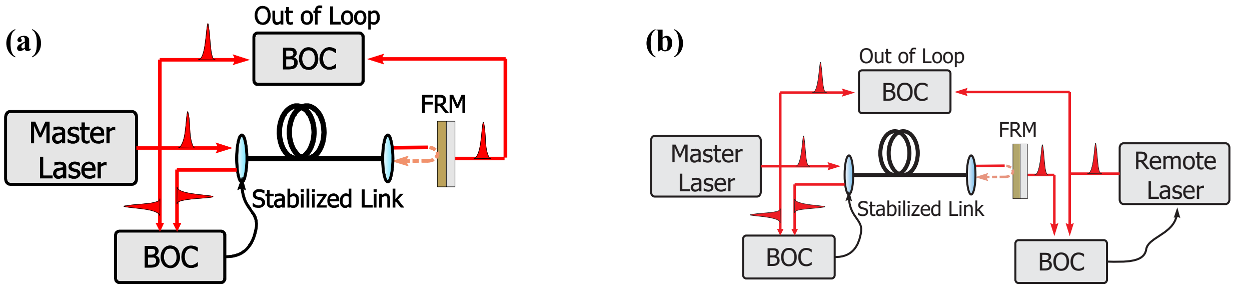

FIG. 2. (a) Schematic of timing link apparatus for measuring performance of the link. (b) Apparatus for measurement of timing transfer from master laser to remote laser.

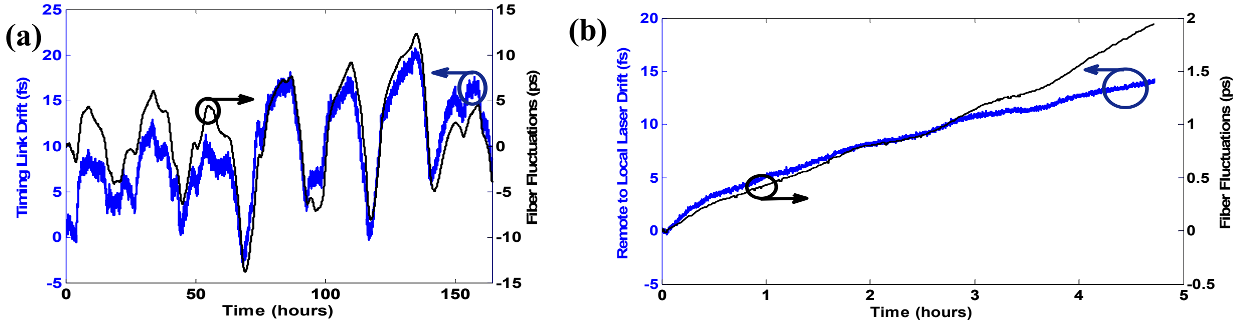

FIG. 3. (a) Out-of-loop drift of the timing link over 168 hours. The blue trace shows the drift of the link output, while the black trace shows the fiber fluctuations for which the link corrected for. (b) Timing transfer performance from local to remote laser through the stabilized link.

Additionally, we demonstrate entirely optical timing transfer from master to remote laser via the timing stabilized fiber link. As shown in FIG. 2(b), the output from the link and of a fraction of the remote laser power is sent to a third BOC, which is used to synchronize the remote laser to the link output. This is done by adjusting an intracavity piezo in the remote laser to keep the remote pulse train phase locked to the link output. The performance of the timing transfer is then assessed by sending the other fraction of power from the remote laser into the out-of-loop BOC, along with some power from the master laser. The residual drift for the timing transfer is only 3.7 fs rms over five hours of operation, as shown by FIG. 2(b). Essentially all of this drift is due to the timing link and/or thermal expansion in the ~1 m scale opto-mechanical construction.

4. Limitations and Analysis

Polarization mode dispersion (PMD), as pertains to ultrafast timing distribution, is the effect whereby the two orthogonally polarized components of a pulse propagate at different group velocities[5]. Therefore, we are concerned with the differential group delay (DGD) between polarizations. This manifests as a breakdown in the fundamental assumption of timing distribution: that the one-way and round-trip propagation delays are related in a known way. The issue is that randomly changing birefringence in the fiber, due to thermal changes or mechanical stresses, changes the polarization of the pulse, and therefore the propagation time, in an unknown way.

The pulse coupled out at the end of the link may evolve through any number of polarization states, and thus propagate along a random mixture of fast-and slow-PMD axes, before reaching the end of the link. The result is that the time required for the pulse to travel through the fiber is unknown, which leads to an observed drift at the output. In practice, one sees a distorted pulse with a center of mass that shifts around in time in an uncontrolled way, even simply by stressing the fiber at one point by hand.

Typical single-mode telecommunications fiber, such as Corning SMF-28e has a specified maximum PMD of 200 fs/√km, although this value varies considerably depending on the manufacturing variations of the particular fiber. However, mechanical stress after installation adds to the innate PMD from the manufacturing process. In practice, this can easily be the most significant source of PMD. For this reason, great care must be taken to avoid coiling or stressing the fiber. Previous implementations of the timing link relied on a piezoelectric fiber stretcher consisting of 40 m of SMF tightly wound around a 5 cm piezo. This device had a measured DGD of 83 fs. Perhaps more troubling is that the act of stretching the fiber induces birefringence which couples the piezo signal to drift in the output, within the closed-loop piezo bandwidth of approximately 1 kHz. As a result, we implemented a combination free-space piezo mirror and motorized delay stage to replace the fiber stretcher.

To directly measure the effect, consider the out-of-loop drift of the timing link as the polarization of the launched pulse is varied with a zero order λ/2 plate placed just before the input fiber collimator. The polarization at the link output was held constant by the polarization controller, while the timing link was locked. We observed 200 fs peak-to-peak drift at the output by rotating the wave plate. By eliminating the stretcher and using jacketed fiber, the PMD is reduced to the average value from the fiber alone, known as $\mathrm{PMD_Q}$, for which Corning specifies only 60 fs/√km. Thus, we expect typical PMD-origin drift of 33 fs peak-to-peak for a 300 meter link.

Fiber non-linearity places a limit on the maximum pulse energy that can propagate in the link without impacting timing transfer. In general, it is desirable to have as high pulse energy as possible in the link to achieve superior signal to noise ratio, for the greatest bandwidth synchronization of devices.

Ideally, neglecting non-linearity, in a dispersion and dispersion slope compensated link, the pulse should return to the same shape as that injected into the link by the laser. However, self-phase modulation (SPM) generates intensity dependant temporal phase that distorts the compression in the DCF. For SMF-28e and DCF, a lossless link, this effect becomes significant at 40 pJ, or 8 mW at 200 MHz pulse repetition rate. The pulse begins to split into two, although the center of mass of the pulse remains unchanged. However, due to the pulse splitting, the BOC transfer function begins to split, with the sign of the slope reversing in the center. This pushes the feedback electronics to track the zero-crossing at earlier times. This effect depends only on SPM and GVD.

At higher pulse energies, the spectral broadening from SPM becomes significant enough for dispersion slope to lead to a timing shift. The spectrum broadens asymmetrically, and the pulse position shifts to earlier time. This process reaches a threshold at about 100 pJ, or 20 mW. However, since we implement DCF with dispersion slope compensation, this effect is largely canceled.

The third non-linear effect impacting timing transfer is intrapulse Raman scattering coupling to the group velocity variation of the fiber. At sufficient pulse energy, Raman scattering induces a Stokes shift, shifting the pulse to longer wavelengths. In turn, the pulse propagates at a different group velocity, due to the GVD slope of the fiber. This process becomes significant also above 100 pJ for the 167 fs pulse from the fiber laser.

To study these non-linear effects, we developed a Split-step non-linear Schrodinger equation code to simulate the propagation of the pulse through a lossless link consisting of 100 m of SMF-28 and equivalent amount of DCF. The simulation captures dispersion, dispersion slope, Raman scattering, SPM and self-steepening. It was conducted for both one-way and round trip propagation through the link. The pulse timing in each case was then calculated by computing the BOC and interpolating the zero-crossing time offset. For comparison, we also calculated the center of mass of the pulse, which we define as the true pulse timing. The effective out-of-loop timing error was then calculated by subtracting the timing shift from half the round-trip propagation from the one-way propagation delay. This is because the free space delay, which is inside the link, imparts twice the delay for the pulse that travels a round trip through the link.

Pulse-splitting from SPM and GVD induce a timing drift, as measured by the BOC, of about 40 fs/mW, beginning at 40 pJ or 8 mW. Above 90 pJ, the pulse is distorted enough to make the BOC transfer function also heavily distorted, and not usable. This effect is the most immediate and severe issue limiting pulse energy in the link since it does not constitute an actual shift in the pulse center of mass, but rather a limitation of the BOC scheme.

At higher pulse energy, intrapulse Raman scattering fundamentally limits the performance. At about 110 pJ, the soliton self-frequency shift begins to shift the pulse center frequency to higher wavelengths. Due to TOD, the group velocity varies by wavelength, and pulse timing shifts as the pulse shifts to the red. This effect is shown by the shifting of the pulse center of mass for different pulse energy, in FIG. 4. Also shown alongside the center of mass is the timing error, as detected by the simulated BOC. In practice, it is desirable to minimize insertion loss variation in the free space delay stage, or to eventually forgo a free space delay stage altogether in favor of a PM fiber stretcher.

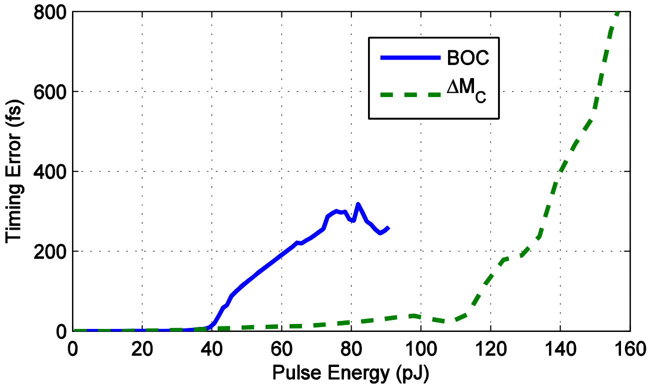

FIG. 4. Timing link error vs. optical power for a simulated link. The error is the difference in pulse timing between a BOC at the link output and an in-loop BOC. Also shown is the shift in the pulse center of mass between link output and round trip.

5. Acknowledgements

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6. References

[1] J. Kim, J.A. Cox, J. Chen, and F.X. Kärtner, "Drift-free femtosecond timing synchronization of remote optical and microwave sources," *Nature Photonics*, vol. 2, 2008, pp. 733-736.

[2] I. Coddington, W.C. Swann, L. Lorini, J.C. Bergquist, Y. Le Coq, C.W. Oates, Q. Quraishi, K.S. Feder, J.W. Nicholson, P.S. Westbrook, S.A. Diddams, and N.R. Newbury, "Coherent optical link over hundreds of metres and hundreds of terahertz with subfemtosecond timing jitter," *Nature Photonics*, vol. 1, 2007, pp. 283-287.

[3] J. Kim, J. Chen, Z. Zhang, F.N.C. Wong, F.X. Kärtner, F. Loehl, and H. Schlarb, "Long-term femtosecond timing link stabilization using a single-crystal balanced cross correlator," *Optics Letters*, vol. 32, 2007, p. 1044.

[4] E.P. Ippen, H.A. Haus, and L.Y. Liu, "Additive pulse mode locking," *Journal of the Optical Society of America B*, vol. 6, 1989, p. 1736.

[5] A. Galtarossa, *Polarization Mode Dispersion*, New York, NY: Springer Science Business Media, Inc., 2005.