One-femtosecond, long-term stable remote laser synchronization over a 3.5-km fiber link

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Abstract: Long-term stable timing distribution over a 3.5-km polarization maintaining (PM) fiber link using balanced optical cross-correlators (BOC) for optical-to-optical synchronization is demonstrated. Remote laser synchronization over 40 hours showed a residual timing jitter and drift of 2.5 fs for the whole locking period and only 1.1 fs integrated from 100 μ Hz to 1 MHz. This result corresponds to the lowest jitter and drift achieved to date for a multi-km fiber link and remote timing synchronization operating continuously over multiple days.

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References and links

1. S. M. Foreman, A. D. Ludlow, M. H. de Miranda, J. E. Stalnaker, S. A. Diddams, and J. Ye, "Coherent optical phase transfer over a 32-km fiber with 1 s instability at 10^{-17} ," *Phys. Rev. Lett.* **99**(15), 153601 (2007).
2. O. Lopez, A. Amy-Klein, M. Lours, C. Chardonnet, and G. Santarelli, "High-resolution microwave frequency dissemination on an 86-km urban optical link," *Appl. Phys. B* **98**(4), 723–727 (2010).
3. K. Predehl, G. Grosche, S. M. F. Raupach, S. Droste, O. Terra, J. Alnis, T. Legero, T. W. Hänsch, T. Udem, R. Holzwarth, and H. Schnatz, "A 920-kilometer optical fiber link for frequency metrology at the 19th decimal place," *Science* **336**(6080), 441–444 (2012).
4. F. R. Giorgetta, W. C. Swann, L. C. Sinclair, E. Baumann, I. Coddington, and N. R. Newbury, "Optical two-way time and frequency transfer over free space," *Nat. Photonics* **7**(6), 434–438 (2013).
5. J. Kim, J. A. Cox, J. Chen, and F. X. Kärtner, "Drift-free femtosecond timing synchronization of remote optical and microwave sources," *Nat. Photonics* **2**(12), 733–736 (2008).
6. The LIGO Scientific Collaboration, "A gravitational wave observatory operating beyond the quantum shot-noise limit," *Nat. Phys.* **7**(12), 962–965 (2011).
7. C. W. Chou, D. B. Hume, T. Rosenband, and D. J. Wineland, "Optical clocks and relativity," *Science* **329**(5999), 1630–1633 (2010).
8. L. Cacciapuoti and Ch. Salomon, "Space clocks and fundamental tests: The ACES experiment," *Eur. Phys. J. Spec. Top.* **172**(1), 57–68 (2009).
9. P. Emma, R. Akre, J. Arthur, R. Bionta, C. Bostedt, J. Bozek, A. Brachmann, P. Bucksbaum, R. Coffee, F. J. Decker, Y. Ding, D. Dowell, S. Edstrom, A. Fisher, J. Frisch, S. Gilevich, J. Hastings, G. Hays, P. Hering, Z. Huang, R. Iverson, H. Loos, M. Messerschmidt, A. Miahnahri, S. Moeller, H.-D. Nuhn, G. Pile, D. Ratner, J. Rzepiela, D. Schultz, T. Smith, P. Stefan, H. Tompkins, J. Turner, J. Welch, W. White, J. Wu, G. Yocky, and J. Galayda, "First lasing and operation of an ångström-wavelength free-electron laser," *Nat. Photonics* **4**(9), 641–647 (2010).
10. M. Altarelli, R. Brinkmann, M. Chergui, W. Decking, B. Dobson, S. Düsterer, G. Grübel, W. Graeff, H. Graafsma, and J. Hajdu, *XFEL: The European X-Ray Free-Electron Laser. Technical Design Report* (DESY, 2006).
11. C. J. Bocchetta and G. De Ninno, *FERMI@ Elettra: Conceptual Design Report* (Sincrotrone, 2007).
12. J. M. Byrd, L. Doolittle, G. Huang, J. W. Staples, R. B. Wilcox, J. Arthur, J. C. Frisch, and W. E. Whit, "Femtosecond synchronization of laser systems for the LCLS," in *Proceedings of International Particle Accelerator Conference* (2010), 58–60.
13. M. Y. Peng, P. T. Callahan, A. H. Nejadmalayeri, S. Valente, M. Xin, L. Grüner-Nielsen, E. M. Monberg, M. Yan, J. M. Fini, and F. X. Kärtner, "Long-term stable, sub-femtosecond timing distribution via a 1.2-km polarization-maintaining fiber link: approaching 10^{-21} link stability," *Opt. Express* **21**(17), 19982–19989 (2013).

14. J. A. Cox, "Sub-femtosecond precision timing distribution, synchronization and coherent synthesis of ultrafast lasers," Thesis, Massachusetts Institute of Technology (2012).
15. A. J. Benedict, J. G. Fujimoto, and F. X. Kärtner, "Optical flywheels with attosecond jitter," *Nat. Photonics* **6**(2), 97–100 (2012).
16. J. Kim, J. Chen, J. Cox, and F. X. Kärtner, "Attosecond-resolution timing jitter characterization of free-running mode-locked lasers," *Opt. Lett.* **32**(24), 3519–3521 (2007).
17. 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," *Opt. Lett.* **32**(9), 1044–1046 (2007).
18. C. Sydlo, M. K. Czwalinna, M. Felber, C. Gerth, T. Lamb, H. Schlarb, S. Schulz, F. Zummack, and S. Jablonski, "Development status of optical synchronization for the european xfel," in *Proceedings of IBIC2013*, Oxford UK (2013).
19. A. H. Nejadmalayeri, F. N. C. Wong, T. D. Roberts, P. Battle, and F. X. Kärtner, "Guided wave optics in periodically poled KTP: quadratic nonlinearity and prospects for attosecond jitter characterization," *Opt. Lett.* **34**(16), 2522–2524 (2009).
20. P. T. Callahan, T. D. Roberts, P. Battle, A. H. Nejadmalayeri, and F. X. Kärtner, "A hybrid integrated balanced optical cross-correlator using PPKTP waveguides," in *Proc. of Conference on Lasers and Electro-Optics* (CLEO, 2013).

1. Introduction

Recently, remarkable progress has been achieved in transferring time/frequency standards [1–4] and relative timing signals [5] over long distances, a technique which has been employed over a wide range of applications including gravitational waves detection [6], geodesy [7] and high precision navigation [8]. Among many other fields, distributing stable timing signals is particularly important for modern large-scale scientific facilities, such as X-ray free-electron lasers (FELs) [9–11]. The operation of FELs depends on the tight synchronization of many microwave and optical devices [5, 12–14], including the electron gun, the photo-injector laser, the RF system in the linear accelerator, the seed laser, and so on. The European XFEL [10], the largest FEL under construction is 3.5 km long. New FEL designs for the Linac Coherent Light Source II are directed towards the production of sub-fs X-ray pulses. To reach the full potential of these facilities, long-term stable remote optical-to-optical laser synchronization with sub-fs precision over several kilometers of link length is desirable. Yet, there are no related reports at this level of timing precision from laser to laser on the kilometer distance scale.

Since a mode-locked laser can simultaneously provide ultralow-noise optical and microwave signals in the form of optical pulse trains, it has the inherent advantage to enable high-precision timing networks that can tightly synchronize multiple microwave and optical sources. We have been advancing such a pulsed approach to timing distribution systems for the past decade [5, 13, 14]. To realize optical-to-optical synchronization [5, 14], we made use of the balanced optical cross-correlation (BOC) locking method [5, 15], because it can easily achieve tight locking with high locking bandwidth. In our previous work [14], the first remote optical-to-optical synchronization experiment was implemented using a 300-m standard single-mode fiber link over 3.5 hours, resulting in 17 fs RMS jitter integrated from 0.01 Hz to 10 MHz. The jitter was mainly attributable to the inherent noise of the master laser, imperfect feedback loop and link instability caused by polarization mode dispersion (PMD). To reduce the PMD-induced timing drift, we later achieved long-term stabilization of a 1.2-km polarization-maintaining (PM), dispersion-compensated fiber link with sub-fs residual timing drift (<0.5Hz) over 16 days of operation [13]. However, due to limitations in the experimental setup, we did not measure the jitter above 0.5 Hz nor realize remote laser synchronization.

In this paper, the remote laser synchronization is extended to a 3.5-km (required for the European XFEL) link, which bears longer-delay for feedback control, higher loss and much more sensitive fluctuation to environmental disturbances. A PM fiber link is also adopted to eliminate the PMD-induced timing jitter. A low phase noise EDFA is used to compensate the splicing and link loss. The link-stabilization feedback loop is optimized to reduce the jitter introduced by master laser inherent phase noise, and the remote-laser-lock feedback loop is separated into two paths to achieve a long-term locking. Finally a remote laser at the end of the link is synchronized to the delivered timing signals over 40 hours of uninterrupted operation, resulting in only 1.1 fs residual jitter integrated from 100 μ Hz to 1 MHz, measured

relative to the master mode-locked laser used for link-stabilization. To the best of our knowledge, this is the lowest timing jitter and drift achieved to date for remote laser timing synchronization, over multi-km distance and multi-day operation. And this level of precision closely meets the timing requirements of the next generation of FELs.

2. Principle of operation

The optical-to-optical remote synchronization includes two parts: link stabilization and remote laser locking. For the link stabilization [13], the optical pulse train (timing signal) generated from a mode-locked laser (master laser), is distributed between two remote locations through a dispersion-slope-compensated PM fiber link. Partial power of the link pulse is back-reflected by an output coupler at the end of the link. And then the timing difference between the round-trip link pulse and the new incoming pulse from the master laser is detected by a BOC, which can generate a timing error signal for feedback to control some variable delay element. It should be noted that the inherent jitter of the master laser, which was not discussed in [13], can also introduce some residual timing errors after link stabilization, if the inherent jitter noise that occurs on a timescale faster than the round-trip link propagation time cannot be ignored. So the performance of link stabilization will be finally limited by the master laser inherent jitter.

Fig. 1. The principle of BOC laser locking.

The output of the stabilized link can be used to lock the remote laser with the BOC locking method. The principle of BOC laser locking can be simply illustrated in Fig. 1. If the pulse trains of two lasers, which have a difference in repetition rate of Δf , are launched into a BOC, then the output voltage is a BOC curve train, with a repetition rate of Δf . This voltage train can be used as a feedback signal to control the PZT of the slave laser. When the voltage falls into the linear range of the BOC curve, the feedback voltage can decrease the repetition rate difference of the two lasers, which then conversely broadens the BOC curve train. As the feedback works continuously, the BOC curve train becomes wider and wider until the output becomes a DC voltage, which, at this point, represents a lock of the slave laser's repetition rate to that of the master laser.

The feedback model for BOC locking is also given in Fig. 1. H_B , H_{PI} and H_{PZT} are the transfer functions of the BOC, the PI controller and the PZT of the slave laser, respectively. The PZT resonant frequency is neglected in H_{PZT} because it is usually much higher the locking bandwidth of the feedback loop. E_B and E_{PI} are the electronic noise of the BOC and PI controller. J_{IM} and J_{IS} are the inherent jitter of the master and slave lasers, and J_R is the

relative jitter between the two lasers at the input port of the BOC. Based on this model, we get the transfer function of the whole system:

$$J_R = \frac{f_r s^2}{f_r s^2 + K_B K_{PI} K_{PZT} (s + 2\pi f_{PI})} (J_{IM} + J_{IS}) + \frac{K_{PI} K_{PZT} (s + 2\pi f_{PI}) E_B + K_{PZT} s E_{PI}}{f_r s^2 + K_B K_{PI} K_{PZT} (s + 2\pi f_{PI})} \quad (1)$$

where K_B (V/fs) and K_{PZT} (Hz/V) are the sensitivities of the BOC and of the slave laser PZT, respectively. K_{PI} and f_{PI} are the gain and corner frequency of the PI controller, and f_r is the repetition rate of the master laser. The two terms in Eq. (1) correspond to the laser inherent jitter and loop electronic noise, respectively. By letting the coefficient modulus of $J_{IM} + J_{IS}$ be $1/\sqrt{2}$, we can calculate the locking bandwidth:

$$f_{Locking} = \sqrt{\frac{K}{2} \left[K - 2f_{PI} + \sqrt{(K - 2f_{PI})^2 + 4f_{PI}^2} \right]} \quad (2)$$

where $K = K_B K_{PI} K_{PZT} / (2\pi f_r)$. It should be noted the locking bandwidth will finally limited by the PZT resonant frequency, so (2) is correct only when the right part is much smaller than PZT resonant frequency. With some typical values such as $K_B = 1$ mV/fs, $K_{PZT} = 10$ Hz/V, $f_r = 100$ MHz, $K_{PI} = 1$, $f_{PI} = 1$ kHz, and 30kHz PZT resonant frequency, $f_{locking}$ can easily exceed 10 kHz. Compared with conventional laser locking based on photodiodes and electronic mixers, it is much easier to get tight locking with a BOC due to its high timing sensitivity. Also, since the optical amplitude noise is well suppressed by the balanced detection, ultra-low residual timing jitter can be achieved by the BOC locking method [15].

3. Experimental setup

The experimental setup of the remote optical-to-optical synchronization is shown in Fig. 2. The whole setup consists of four sections: link-stabilization, link-transmission, remote laser lock, and out-of-loop measurement. Both the master and remote laser are manufactured by Onefive (Origami-15). The master laser operates with a 216.6665 MHz repetition rate, 150 fs pulse width, 1554.7 nm center wavelength and + 22.4 dBm average output power, while the remote laser has a 216.6685 MHz repetition rate, 172 fs pulse width, 1553.4 nm center wavelength and + 22.1 dBm average output power. These two lasers have ultra-low phase noise; our measurement results have shown that their integrated timing jitter above 10 kHz is below 100 as. The repetition rate of the master laser was locked to a microwave reference (Agilent E8257D) with a 10-Hz locking bandwidth, so as to reduce its timing drift below 10 Hz. The repetition rate of the remote laser can be coarsely tuned by a computer if it is too far away (out of the PZT tuning range) from that of the master laser.

In the link-stabilization section, the pulse train from the master laser was divided up by PBS 3 into pulse trains in the reference path and in the link path. The reference path is only 4 cm, to minimize environmental instability. The link path consists of a 45° Faraday rotator, a half-wave plate, two polarizers, a collimator, a motorized optical delay line (ODL), a fiber stretcher, a 3.5-km PM link, a polarization-maintaining erbium-doped fiber amplifier (PM-EDFA), and a 90/10 transmission/reflection fiber mirror. In order to guarantee that the forward and backward link transmission introduce the same amount of jitter, the pulse must travel along the same polarization axis; the 45° Faraday rotator before the fiber link is therefore necessary to introduce a 90° round-trip polarization rotation, so as to let the reflected link pulse reach the in-loop BOC 1. The half-wave plate aligns the input polarization direction with the slow-axis of the PM link.

Fig. 2. Experimental setup for remote optical-to-optical synchronization. PBS: polarization beam splitter cube; SM: silver mirror; $\lambda/2$: half wave plate; $\lambda/4$: quarter wave plate; FR: 45° Faraday rotator; Pol: polarizer; DBS: dichroic beam splitter; DM: dichroic mirror; PPKTP: periodically-poled KTiOPO_4 ; BPD: balanced photo detector; BOC: balanced optical cross-correlator; 3.5-km PM Link: 3.5 km polarization-maintaining dispersion compensated fiber link; PM-EDFA: polarization-maintaining erbium-doped optical fiber amplifier; 90/10 FM: 90/10 transmission/reflection fiber mirror; PI^2D controller: proportional-double-integral-differential controller; PI controller: proportional-integral controller; DAQ: data acquisition card; LPF: 1-Hz low pass filter; SSA: signal source analyzer; PC: personal computer.

The link stabilization loop begins with the in-loop BOC, which consists of a single 4-mm periodically-poled KTiOPO_4 (PPKTP) crystal operated in a double-pass configuration with appropriate dichroic elements [16, 17]. The balanced photo-detector (BPD, Newport 2307) has a 3-dB bandwidth of 1 MHz. The output voltage of the proportional-double-integral-differential (PI^2D) controller (Vescent D2-125) was divided into two paths. The first path was amplified by a high voltage amplifier (Menlo Systems, HVA 150) to control a PM fiber stretcher (Optiphase PZ3), which has a sensitivity of 6.4 fs/Volts. The fiber stretcher was responsible for compensating the fast noise in the link; its response was limited to below 1 kHz due to the locking bandwidth. The second path was sampled by a data acquisition (DAQ)

card, and used to control the motorized ODL (General Photonics MDL-002) through a Labview program. The motorized ODL has a tuning range of 560 ps, which is more than sufficient to compensate the slow drift of the link.

The 3.5-km PM link, which was fabricated by OFS Fitel, consists of 2946 m of standard PM 1550 panda-style fiber and 511 m of custom dispersion-compensating PM fiber (PM-DCF). The PM-DCF has a measured birefringence of 2.9×10^{-4} , 0.4 dB/km loss and 1520 nm cut off wavelength. At 1550 nm, the slow axis has a dispersion and dispersion slope of -102.5 ps/(nm·km) and -0.33 ps/(nm²·km), respectively, which can compensate for the dispersion and dispersion slope of the PM 1550 fiber simultaneously. To minimize losses due to its small mode-size ($A_{\text{eff}} = 22 \mu\text{m}^2$), the PM-DCF was spliced to an intermediate bridge fiber (PM Raman fiber) before splicing to PM 1550. The total polarization extinction ratio of the link is only 16.7 dB; to improve this performance, two polarizers were placed before and after the link. For operation near 1554.7 nm, the residual link dispersion was compensated by adding 5 m of PM Raman fiber to achieve a minimum pulse width of 400 fs at the output of EDFA.

The PM-EDFA is a customized bidirectional PM EDFA. The input power at the collimator was + 8 dBm. The total loss of the link was about 8 dB, so we had + 0 dBm input power for the forward direction of the PM-EDFA. The EDFA was operated with a pump current of 850 mA and the forward output power was + 13dBm. + 3 dBm of power was reflected back by the fiber mirror, and the backward output power was also around + 13 dBm, which is close to the onset of the fiber nonlinearity.

In the remote laser lock section, the link output was combined with the remote laser output using PBS 4. Then the two pulse trains were launched into a BOC to generate the timing error signal for feedback control. The BOC output voltage was first filtered by a proportional-integral (PI) controller (New Focus LB1005). After that, the voltage was separated into two paths; the first path was sent directly to a home-built voltage adder without amplification, to guarantee enough phase margin for stable locking; and the second path was sampled by a DAQ card and analyzed by a Labview program, which outputs a DC offset voltage. After amplification, this signal was responsible for large range compensation. Finally the voltage adder output was used to drive the PZT in the remote laser, which has a sensitivity of 17.4 Hz/V.

After stabilizing the link and synchronizing the repetition rate of the remote laser, the original pulse trains of the master and remote laser were combined by PBS 5 and launched into BOC 3, to evaluate the performance of the whole setup by measuring the residual timing jitter of link and remote laser locked by the BOC technique.

Temperature stabilization and vibration isolation of the free-space optics are important to measure the true residual jitter accurately. A $900 \times 1200 \times 4.8$ mm super invar face sheet was placed on top of a water-cooled breadboard, which was controlled by a chiller (Lauda RP 845C) to stabilize the temperature of the invar face sheet within $\pm 0.1^\circ\text{C}$ variation. All the free-space components were fixed on this invar sheet to reduce the measurement errors induced by temperature changes; the thermal expansion coefficient of this sheet is only $0.63 \mu\text{m}/\text{m}\cdot^\circ\text{C}$ for -55 to $+95^\circ\text{C}$. Lead foam was placed underneath the water-cooled breadboard to dampen table vibrations. A two-layer enclosure with acoustic heavy foil for the inner layer and high-density polyethylene (HDPE) for the outer layer was also built to cover the whole setup (including the link) and to isolate the setup from acoustic noise.

4. Results and discussion

After stabilizing the link and locking the remote laser, we evaluated the performance of remote optical-to-optical synchronization. First, the timing sensitivities of the three BOCs were measured. For BOC 1, with + 16 dBm of reference power and + 2 dBm of link reflected power, the sensitivity of the BOC curve, shown in red in Fig. 3(a), is about 14 mV/fs using the high gain setting (2×10^6 V/A) of the BPD. The timing resolution is limited by the detector electronic noise and the corresponding integrated jitter of the noise floor is $J_{NF} = 137$ as. With + 10 dBm of link output power and + 18 dBm of remote laser power, the curve of

BOC 2 is also shown in Fig. 3(a) (blue curve). The sensitivity is 6.2 mV/fs ($J_{NF} = 23$ as, shot noise limited) using medium gain setting (1×10^5 V/A) on the BPD and can reach 124 mV/fs ($J_{NF} = 20$ as, shot noise limited) when using the high gain setting. These high sensitivities indicate that both of the two BOCs were capable of tight locking. The out-of-loop BOC curve is given in Fig. 3(b), with +17 dBm master laser power and +18 dBm remote laser power, a sensitivity of 105 mV/fs ($J_{NF} = 5$ as, shot noise limited) at medium gain or 2.1 V/fs ($J_{NF} = 4$ as, shot noise limited) at high gain was reached due to the high input power of the two arms.

Fig. 3. Remote optical-to-optical synchronization measurement results. (a) link-stabilization and remote laser lock BOC curves; (b) out-of-loop BOC characteristic; (c) measured jitter spectral density from SSA and its corresponding integrated timing jitter; (d) out-of-loop drift over 40 hours and the corresponding ODL delay and PZT offset frequency; (e) relative humidity and relative temperature change inside the enclosure; (f) complete jitter spectral density from 7 μ Hz to 1 MHz and its corresponding integrated timing jitter.

The output of the BOC 3 was sent to the signal source analyzer (SSA, Agilent E5052B), to measure the power spectral density of the residual timing jitter above 1 Hz. The result is given in Fig. 3(c). The total integrated jitter from 1 Hz to 1 MHz is about 0.91 fs. The bump between 1 kHz and 10 kHz was mainly due to residual link-stabilization jitter induced by the

phase noise of the master laser and also due to additional electronic noise that was amplified during the tight remote BOC laser locking.

In order to measure the low-frequency jitter, the BOC 3 output voltage was first filtered by a 1-Hz low pass filter (LPF) to avoid aliasing, and then recorded by a DAQ card with 2-Hz sampling rate. Optical-to-optical synchronization over 40 hours was achieved without interruption. The recorded data for the out-of-loop drift, the corresponding ODL delay, and the DC offset voltage of the remote laser PZT, which has been changed to frequency by multiplying by the PZT sensitivity, are shown in Fig. 3(d). Overall, the ODL corrected 17 ps of link fluctuations and the BOC laser locking corrected for 350 Hz of repetition rate drift. The remaining timing drift at the out-of-loop BOC showed a maximum deviation of about 10 fs and an RMS value of 2.3 fs. During the period from the 8th to the 18th hour, and from the 25th to the 40th hour, the RMS drift is below 0.7 fs.

Figure 3(e) shows the relative humidity and temperature change in the enclosure during the measurement. The temperature fluctuation was $\pm 0.2^\circ\text{C}$ and the maximum variation of the relative humidity was 4%. It can be found that the ODL delay is correlated with both the temperature and relative humidity, because temperature can change the link length and humidity can change the refractive index of the fiber [18]. We also found that the output power of the ODL fluctuates at different delay positions, and the maximum fluctuation within the full tuning range is 8%. This power fluctuation can be misjudged by the link-stabilization BOC as a timing error and finally cause a timing jitter in the out-of-loop measurement results. Also, the measurements indicate that there are still some uncompensated beam paths in the link-stabilization feedback loop. The out-of-loop drift in Fig. 3(d) was attributable to ODL power fluctuations, imperfect feedback loop, and as well as the instability of free space components in the out-of-loop measurement section.

By taking the Fourier transform of the link drift data in Fig. 3(d) and then connecting it with the SSA measurement results in Fig. 3(c), we obtained the complete jitter spectral density from 7 μHz to 1 MHz, as shown in Fig. 3(f). It can be seen that the low frequency jitter (<1 Hz) is mostly contributed by the components below 40 μHz . The calculated integrated jitter is also given in Fig. 3(f), and the integrated jitter from 100 μHz to 1 MHz is about 1.1 fs. Compared with our previous results [14], an order-of-magnitude improvement was obtained for link length, remote laser locking time and residual jitter, simultaneously. To the best of our knowledge, this is the lowest timing jitter result to date for remote laser timing locking with multi-km link length and multi-day uninterrupted operation time.

In order to achieve sub-100 as residual jitter for the link stabilization and sub-fs residual timing jitter for the remote laser synchronization over the full frequency range, some prediction mechanism needs to be introduced into the link-stabilization feedback loop to eliminate the time-delay resonance due to the link round-trip transmission. The remote laser lock loop needs to be deeply analyzed to target the additional noise source between 1 kHz and 10 kHz after tight locking. Furthermore, the power fluctuation of the ODL needs to be decreased. This may be realized by replacing the ODL with a free space motorized stage and optimizing the alignment. The slow control program in link-stabilization also needs to be optimized to find the source of the uncompensated errors. Lastly, the temperature drift can also be further suppressed by using an integrated BOC [19, 20].

5. Conclusion

We have successfully demonstrated long-term stable remote optical-to-optical synchronization of lasers for 40 hours, via a 3.5-km PM fiber link, to match the length required for the European XFEL. The timing drift at 10-hour time scale is mainly attributable to the ODL-induced link power fluctuation and is expected to be reduced by replacing the ODL with an alignment-optimized motorized stage. From the 8th to the 18th hour, and in the last 15 hours, the RMS drift is below 0.7 fs; and the RMS timing jitter integrated from 100 μHz to 1 MHz is only 1.1 fs. This is the lowest jitter result that has ever been achieved for remote laser timing synchronization with multi-km link length and multi-day uninterrupted locking time. Continuing towards sub-100-as precision for link stabilization and sub-fs for

remote laser synchronization, ongoing work is focused on suppressing the power fluctuations in the link power, optimizing the feedback loops for both link and remote laser locking, and developing an all-integrated BOC to greatly reduce the temperature-dependent drift while simultaneously increasing BOC timing sensitivities for tighter locking of feedback loops.

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