Synchronization of mode-locked femtosecond lasers through a fiber link

Darren D. Hudson, Seth M. Foreman, Steven T. Cundiff, and Jun Ye

JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440 and Department of Physics, University of Colorado, Boulder, Colorado 80309-0390

Received February 24, 2006; accepted March 26, 2006; posted April 11, 2006 (Doc. ID 68445)

Two mode-locked femtosecond fiber lasers, connected via a 7 km fiber link, are synchronized to an rms timing jitter of 19 fs, observed over the entire Nyquist bandwidth (half of the 93 MHz repetition frequency). This result is achieved in two steps. First, active cancellation of the fiber-transmission noise reduces timing jitter caused by path length fluctuations to a record level of 16 fs. Second, using a wide bandwidth interactivity actuator, the slave laser is synchronized to the incoming stable pulse train from the reference laser to within 10 fs. These results are confirmed by an optical cross-correlation measurement performed independently of the feedback loop operated in the microwave domain. © 2006 Optical Society of America

OCIS codes: 320.7160, 120.3930, 140.4050.

In recent years synchronization of the repetition frequency of two independent mode-locked lasers has been pushed to an unprecedented precision of <1 fs.[1–3] While most of these efforts have been directed at Ti:sapphire lasers, there has been significant recent progress in this area using fiber-based systems such as erbium-doped fiber lasers,[4] which are more challenging for stabilization than the solid-state laser systems. Some applications of synchronized lasers, such as coherent pulse synthesis[5] and precise pump–probe experiments,[6] use collocated lasers with direct optical links of only a few meters. For many applications, however, it is necessary to have remotely located lasers separated by distances ranging from tens of meters to several kilometers.[7] Transmitting optical pulses over kilometer-scale distances places strict limits on the optical system; the most feasible way is using telecommunications grade optical fibers, which have low loss (<0.25 dB/km) at wavelengths around 1550 nm. Erbium-doped fiber lasers, which emit light centered at 1550 nm, are thus employed to utilize this transmission medium. Optical fibers, however, are sensitive to environmental perturbations such as acoustic vibrations, thermal fluctuations, and mechanical stresses. The resultant optical path length fluctuations introduce timing jitter on the pulse train, which must be canceled if a remotely located laser is to be synchronized to the incoming pulse train. In this Letter we demonstrate that active cancellation of this fiber transmission path noise and a large feedback bandwidth allow, for the first time to our knowledge, tight synchronization of two fiber lasers over kilometer-scale transmission distances. We present an out-of-loop time-domain analysis of the timing jitter via optical cross correlation, which allows sensitive measurement of the jitter and verifies the frequency-domain in-loop measurements.

The two fiber lasers used in this experiment are both erbium-doped, ring cavity design lasers with a nonlinear polarization rotation scheme as the mode-locking mechanism.[8] The free-running reference laser, which has a repetition frequency of 31 MHz, is enclosed in an acrylic box that is mounted on an optical breadboard. The fiber in the laser cavity is environmentally isolated by securing the fiber to lead-backed foam inside the enclosure. The slave laser, which has a repetition frequency of 93 MHz, has two crucial intracavity actuators, an electro-optic modulator (EOM), and a piezoelectric transducer (PZT). The intracavity EOM has a servo bandwidth of over 200 kHz, allowing for local synchronization with a timing jitter of 10 fs.[4] The intracavity PZT has a long dynamic range of 14 μm, which allows for locking times of greater than 12 h.

The next element of synchronization is the fiber link between the two lasers. We used two different fiber links to test our method of actively canceling the group delay noise introduced on the pulse train by the fiber: an installed 6.9 km fiber in the Boulder area (known as BRAN) and a 4.5 km spool of dispersion-shifted fiber (DSF). The timing jitter introduced by either of these two fiber links is canceled (to the same degree for either link) by a PZT fiber stretcher that has a large dynamic range.[9,10] We used these fiber links to simulate the timing jitter that the pulse train would experience in a real-world implementation of this system. In this demonstration we use the configuration shown in Fig. 1, where we cancel the round-trip jitter of the link instead of the one-way jitter. However, for transmission to a physically different location, a portion of the light at the remote end must be retroreflected and detected at the local end to derive the timing jitter information of the fiber link.[11] A truly remote system incorporating retroreflection with a fiber link half as long as ours is expected to perform at the same level as the measurements that we report here.

These two elements—fiber transfer and synchronization—are combined to achieve the synchronization of the two lasers over a kilometer-scale fiber link. Figure 1 shows a high-level diagram of the experiment. Active noise cancellation is used to deliver a highly stable pulse train over the fiber link. Once this is accomplished, the intracavity actuators in the slave laser synchronize its repetition frequency to that of the incoming pulse train.

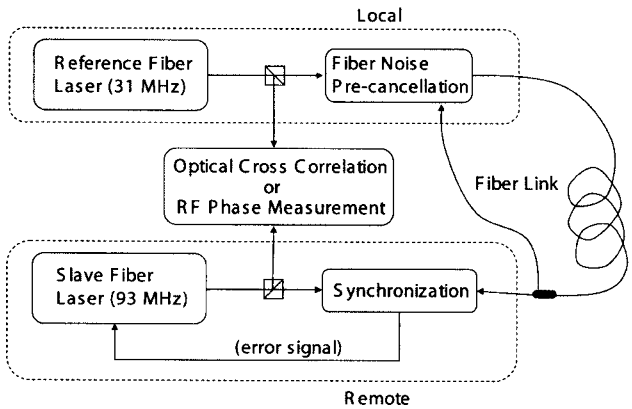

Fig. 1. Schematic of the transfer and local synchronization setup. The synchronization loop compares the incoming pulse train, which is stabilized via a fiber noise cancellation loop, with the slave laser's pulse train; the resulting error signal is fed back to the intracavity EOM and PZT of the slave laser. The cross correlation is performed locally.

We characterize the residual timing jitter of the synchronization by using a crossed-beam, background-free, optical cross correlation of the two lasers' pulse trains. The two pulse trains are focused onto a $LiIO_3$ crystal (type-I phase matching), which generates sum frequency light (SFG) when the two pulses overlap in time and space. To achieve temporal overlap, we use two phase-locked loops that operate at two different timing resolutions.[1] A course-timing loop operates at the fundamental frequency of 93 MHz, while a higher-resolution loop operates at 7.6 GHz (80th harmonic of the fundamental). A phase shifter in the fundamental frequency loop allows course-timing adjustments such that temporal overlap between the two pulse trains can be found. Since the slave laser's repetition frequency is three times that of the reference laser, only every third pulse from the slave laser overlaps a pulse from the reference laser. Once a SFG signal is observed on a photomultiplier tube (PMT), we measure the total cross-correlation width to calibrate the data. We then transfer control from the fundamental frequency loop to the 7.6 GHz loop. A phase shifter in the high-harmonic loop allows us to finely tune the time overlap of the pulses to position the SFG signal at the steepest point of the cross-correlation slope to obtain the most sensitive measurement of the pulse timing jitter, which is proportional to the amplitude fluctuations of the SFG signal. The fluctuations are monitored through a 50 MHz low-pass filter to determine the timing jitter within an integration bandwidth up to the Nyquist frequency.

It is important to note that the cross correlation is performed on the same optical table that holds the two lasers used in the experiment. This configuration allows a direct comparison of the two lasers, which reveals the timing jitter due to both the transmission path and the slave laser's locking ability. This measurement verifies our synchronization capability over the fiber network. For a successful implementation of true remote synchronization, the only change is to detect the retroreflected light through the transmission path, as discussed above.

To characterize the performance of the servo loops for synchronization over a fiber link, we first analyze the Fourier frequency spectrum of the error signal of the phase-locked loops. The first step is to analyze the timing jitter between the two lasers when synchronized locally (i.e., without a kilometer-scale fiber link connecting the two). The residual in-loop timing jitter between the two pulse trains is measured by way of the residual phase noise fluctuation between the two repetition frequency signals in the Fourier frequency spectrum, which can be converted into a timing jitter spectral density. Figure 2(a) shows the jitter spectral density out to 100 kHz and a corresponding integrated jitter of 10 fs.

Next, we characterized the jitter of the fiber-link transfer of the pulse train from the reference laser. The error signal in this case is derived from mixing the local rf signal with the rf signal from a photodetector that detects the transmitted light; this error signal is then fed back to the PZT fiber stretcher, which has a resonance around 18 kHz. This wide bandwidth actuator yields an improvement over previous measurements[10]; we now achieve approximately 16 fs of timing jitter for either the BRAN or DSF fiber, integrated over 1 Hz to 100 kHz, as can be seen in Fig. 2(b). Importantly, we measure an out-of-loop error signal by using independent photodetectors for the combined transfer and synchronization. This is shown in Fig. 2(c), with a total jitter of 19 fs, integrated over 1 Hz to 100 kHz.

Next, we improve the jitter measurement by using an out-of-loop optical cross correlation between the two pulse trains. This approach is advantageous, since it provides a highly sensitive detection of timing jitter without electronic noise contributions, and it also provides an independent assessment of the

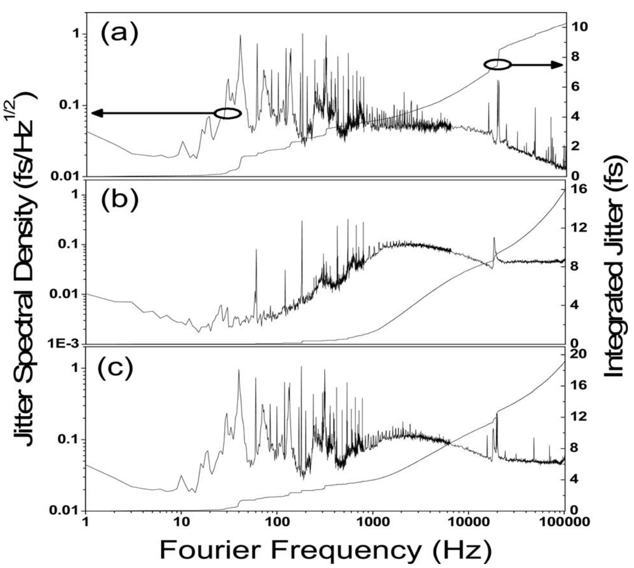

Fig. 2. In-loop error signal for (a) local synchronization, (b) fiber noise cancellation, and out-of-loop error signal for (c) long-distance synchronization. All plots are shown over a 1 Hz to 100 kHz integration bandwidth. The fiber noise cancellation loop has 16 fs of timing jitter, the local synchronization has 10 fs of timing jitter, and the long-distance synchronization has a timing jitter of 19 fs.

system performance out of the servo loop. The local synchronization result measured by the optical cross correlation is shown in Fig. 3(a). The conversion coefficient of the timing jitter (phase noise) to the amplitude fluctuations of the SFG signal is precalibrated, and thus, we can determine the rms timing jitter directly from the amplitude fluctuations of the SFG signal. This measurement is taken in a bandwidth equal to the Nyquist frequency (50 MHz), which ensures that it is an accurate representation of all of the noise on the repetition frequency synchronization. We note that the direct jitter measurement from the optical cross correlation agrees with that from the indirect approach of integrating the residual phase noise of the error signal in the feedback loop over a 100 kHz bandwidth, indicating that there is no significant noise contribution beyond 100 kHz.

Finally, we characterize the timing jitter of the synchronization over the fiber link (DSF) by using the optical cross correlator. The cross correlation between the two lasers reveals 19 fs of timing jitter observed over the Nyquist frequency bandwidth as can be seen in Fig. 3(b), in agreement with the result shown in Fig. 2(c). The total timing jitter is essentially the root-square sum of the residual jitters from the local synchronization and the fiber transfer. It is interesting that the phenomenon of multiple pulsing, observed on the reference fiber laser, proved to be detrimental to the synchronization results. By varying the pump power and polarization state of the laser, the number of multiple pulses can be controlled and the extra pulses can be systematically eliminated. In experiments in which the reference laser was multiple pulsing, the cross-correlation data showed much higher timing jitter, even though the in-loop error signal analysis indicated tight synchronization. This observation highlights the importance of using optical cross correlation and the danger of relying on the in-loop error signal. For cases in which the laser had several extra pulses (i.e., more than four pulses), the timing jitter under the tight lock condition was so severe that the cross-correlation signal explored its full range of 165 fs. By selecting an appropriate polarization state of the laser, however, we were able to eliminate the multiple pulsing and achieve the best timing jitter results.

The timing jitter suppression is currently limited by the bandwidth of the actuators in the system: the PZT fiber stretcher, the intracavity EOM, and the intracavity PZT. However, the fundamental limits imposed by Johnson (thermal) noise on the rf amplifiers

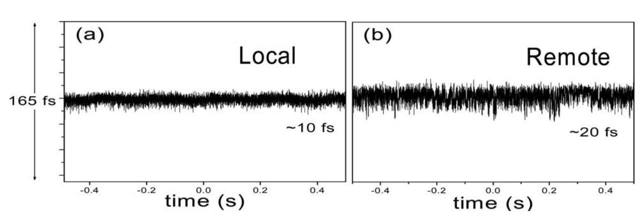

Fig. 3. Optical cross-correlation measurement of the timing jitter for (a) local synchronization, and (b) long-distance synchronization. Both traces show the rms timing jitter within the Nyquist bandwidth (50 MHz).

and shot noise on the photocurrent are quickly being approached. Both of these effects contribute white phase noise that scales inversely with the rf signal's power. The synchronization over the fiber link employs the weakest optical power owing to losses in the fiber after several kilometers of transmission, which leads to $P_{\text{signal}}=-48$ dBm for the rf signal from the photodetector, while the photodetector in the local system has sufficient incident light to generate ~−30 dBm in the 7.6 GHz carrier. For this carrier frequency at an rf power level of −48 dBm, Johnson and shot noise yield phase noise floors of −129 and −132 dBc/Hz. Integrating these noise floors over the slave laser's actuator bandwidth of 200 kHz yields timing jitters of 4.7 and 3.3 fs, respectively. Employing fast photodetectors that can receive larger optical powers will lower these fundamental noise limits.

In summary, we have demonstrated synchronization through a 7 km fiber link of two femtosecond fiber lasers at a record timing jitter level of 19 fs over the Nyquist bandwidth. This measurement was performed via an optical cross correlation, which provides the most sensitive measurement of timing jitter. We achieved this result by combining the fiber transfer of a reference laser with the synchronization of a slave laser using a fast intracavity actuator.

We thank K. Holman for useful technical contributions made at the early stages of this work. This work is supported by the U.S. Office of Naval Research, NASA, and the National Institute of Standards and Technology. J. Ye and S. T. Cundiff are staff members in the NIST Quantum Physics Division. D. Hudson's e-mail address is hudsond@jilau1.colorado.edu.

References

1. R. K. Shelton, S. M. Foreman, L.-S. Ma, J. L. Hall, H. C. Kapteyn, M. M. Murnane, N. Notcutt, and J. Ye, Opt. Lett. **27**, 312 (2002).
2. A. Bartels, S. A. Diddams, T. M. Ramond, and L. Hollberg, Opt. Lett. **28**, 663 (2003).
3. 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, and F. X. Kaertner, Opt. Lett. **28**, 947 (2003).
4. D. D. Hudson, K. W. Holman, R. J. Jones, S. T. Cundiff, and J. Ye, Opt. Lett. **30**, 2948 (2005).
5. R. K. Shelton, L.-S. Ma, H. C. Kapteyn, M. M. Murnane, J. L. Hall, and J. Ye, Science **293**, 1286 (2001).
6. A. C. Yu, X. Ye, D. Ionascu, W. X. Cao, and P. M. Champion, Rev. Sci. Instrum. **76**, 114301 (2005).
7. H. de Riedmatten, I. Marcikic, W. Tittel, H. Zbinden, D. Collins, and N. Gisin, Phys. Rev. Lett. **92**, 047904 (2004).
8. L. E. Nelson, D. J. Jones, K. R. Tamura, H. A. Haus, and E. P. Ippen, Appl. Phys. B **65**, 277 (1997).
9. K. W. Holman, D. J. Jones, D. D. Hudson, and J. Ye, Opt. Lett. **29**, 1554 (2004).
10. K. W. Holman, D. D. Hudson, J. Ye, and D. J. Jones, Opt. Lett. **30**, 1225 (2005).
11. J. Ye, J. Peng, R. Jones, K. Holman, J. Hall, D. Jones, S. Diddams, J. Kitching, S. Bize, J. Bergquist, L. Hollberg, L. Robertsson, and L. Ma, J. Opt. Soc. Am. B **20**, 1459 (2003).