Remote transfer of a high-stability and ultralow-jitter timing signal

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Transfer of a high-stability and ultralow-jitter timing signal through a fiber network via a mode-locked fiber laser is demonstrated. With active cancellation of the fiber-transmission noise, the fractional instability for transfer of a radio-frequency signal through a 6.9- (4.5-) km round-trip installed (laboratory-based) fiber network is below $9(7)\times 10^{-15}\ \tau^{-1/2}$ for an averaging time $\tau \geqslant 1$ s, limited by the noise floor of the frequency-counting system. The noise cancellation reduces the rms timing jitter, integrated over a bandwidth from 1 Hz to 100 kHz, to 37 (20) fs for the installed (laboratory-based) fiber network, representing what is to our knowledge the lowest reported jitter for transfer of a timing signal over kilometer-scale distances using an installed (laboratory-based) optical-fiber network. © 2005 Optical Society of America

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The development of optical atomic clocks with excellent short-term stability[1,2] has created a need for high-fidelity remote frequency transfer that preserves this stability. Such transfer would facilitate the comparison of frequency standards developed in different laboratories. These comparisons would provide a measure of the relative instability and systematic shifts between the systems as well as provide tests of fundamental physics such as searching for time variation of fundamental constants.[3,4] There are also a number of applications that would benefit from the transfer of a timing signal that exhibits ultralow jitter, including timing distribution throughout a linear accelerator facility for the generation of ultrashort x-ray pulses for pump–probe experiments.[5] Long-baseline astronomical observations also require the use of low-jitter timing distributions for coherent data collection among remotely located telescopes.[6]

We report high-stability transfer of a radio-frequency (rf) timing signal over an optical-fiber network with active cancellation of the fiber-transmission noise. The rf signal is transferred by use of harmonics of the pulse repetition frequency of a passively mode-locked fiber laser operating at 1.5 μm. Previously we demonstrated that the passive transfer of a harmonic of the laser repetition frequency has a fractional instability of $<3\times 10^{-14}$ for a 1-s averaging time.[7] The pulse train from the laser was transmitted through two dark, standard telecom fibers (SMF-28) installed in the Boulder Research and Administration Network (BRAN),[8] with a 6.9-km round trip and nine breakout panels. We found that we achieved the best performance by minimizing the average optical power incident upon the photodetector used to recover the rf signal while we maintained a sufficient signal-to-noise ratio for this signal. This procedure reduces instability introduced by the photodetector, which arises from the conversion of amplitude noise in the pulse train to phase noise in the rf signal.[9] Therefore it is critical to keep the pulses received after transmission as short as possible, because shorter pulses provide greater rf signal power after photodetection for a given average optical power. However, we found that the group-delay dispersion of the BRAN fiber dramatically stretches the pulses to ~1 ns.

In this Letter we demonstrate several important advances in the transfer of pulsed signals over a fiber link that enable this type of transfer to be used for both precision frequency metrology and highly stable timing synchronization. First, we implemented dispersion control of the fiber, resulting in transmitted pulses near the detector resolution of 40 ps. We accomplished this by use of either dispersion-compensation fiber (DCF) to prechirp the pulses before their transmission through the BRAN or dispersion-shifted fiber [(DSF), which has negligible dispersion] in place of the BRAN fiber. In both cases the transmitted pulses are sufficiently short to eliminate photodetector contributions to the instability. Second, we performed fast, active noise cancellation to remove group-delay variations caused by fluctuations in the transmission path. This reduces the instability of transfer to the measurement noise floor for averaging times of $\geqslant 1$ s. Third, we completed studies of noise occurring on faster time scales that will be crucial for potential timing-synchronization applications that are sensitive to this fast noise. The residual timing jitter, integrated from 1 Hz to 100 kHz, is of the order of 10 fs for kilometer-scale transmission lines. Noise faster than 100 kHz is irrelevant, as the typical tracking bandwidth of a local oscillator at the receiving end of the frequency-distribution network is normally <100 kHz. Though active stabilization was implemented by others previously to reduce the frequency instability of transfer over optical fibers for time scales of >100 s,[10] to our knowledge the only previously reported control of the timing jitter was limited by a feedback-loop time constant of ~10 s and a measurement resolution of

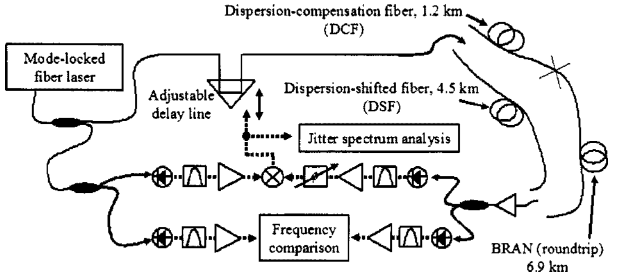

Fig. 1. Schematic of the setup for detecting and stabilizing jitter introduced during the transfer of fiber-laser pulses. The fiber-transmission link is either the BRAN preceded by the DCF or the DSF. The signals from the upper pair of detectors are set in quadrature with the phase shifter and mixed to determine the phase noise of the transfer. The phase error is fed to the adjustable delay line for noise cancellation. The lower set of detectors is used for out-of-loop determination of the frequency instability of the transfer.

400 fs, integrated over a bandwidth of only 100 Hz.[11]

Figure 1 shows the experimental setup used to measure the fiber-transmission noise and actively cancel it. The output of the free-running fiber laser is split into two portions. One portion is transmitted through an adjustable delay line and then through the fiber-transmission link. The adjustable delay line, the details of which are discussed below, is used to cancel the fiber noise. The fiber link is either the 6.9-km round trip of the BRAN fiber preceded by 1.2 km of DCF, the combination of which has a net dispersion of <3 ps/nm, or a 4.5-km length of DSF with a net group-delay dispersion of <18 ps/nm. The BRAN round trip is implemented with two fibers instead of a retroreflector and an optical circulator because the optical circulator increases the transfer instability by a factor of 2, both with and without active noise cancellation, possibly as a result of polarization mode dispersion. An erbium-doped fiber amplifier is used to compensate for losses in the fiber link. The second portion of the fiber-laser output provides a reference against which to measure noise introduced by the transmission link.

The reference and transmitted pulse trains are each detected on two photodetectors. We then filter the resultant rf signals to select the desired harmonic of the laser repetition frequency. We measure the jitter (or phase noise) introduced during transmission by mixing the 81st harmonic (7.84 GHz) of the transmitted and reference signals in quadrature. The measured phase noise is fed to the adjustable delay line, with appropriate gain and filtering, to apply corrections that cancel the fiber noise. Spectral analysis of the jitter is accomplished with a fast-Fourier-transform spectrum analyzer. The other two signals are compared outside the stabilization loop at the 8th harmonic (774 MHz) of the laser repetition frequency. A frequency-counting technique is used that provides a measure of the frequency instability introduced by the transmission.[7]

The BRAN fiber preceded by the DCF yields transmitted pulses that are ~60 ps, most likely limited by higher-order dispersion. The short pulses provide a high signal-to-noise ratio for the recovered rf signal with an average optical power sufficiently low (~30 μW) to eliminate noise caused by the photodetection. The remaining transmission noise is canceled by the adjustable delay line, which consists of two elements in series. A free-space path length terminated with a retroreflector actuated by an electrodynamic shaker is followed by a piezoactuated fiber stretcher. The shaker provides a large range of motion (a few millimeters), and the piezoactuated fiber stretcher extends the servo bandwidth to ~100 Hz. The bandwidth is limited by a resonance in the fiber stretcher at ~5 kHz. We are not yet affected by the fundamental limitation imposed by the transit time through the fiber path.

The frequency-counting technique in Fig. 1 is used to measure the fractional-frequency instability introduced by the BRAN as a function of averaging time, represented by the Allan deviation in Fig. 2. The instability in the absence of active noise cancellation is $\sim 3\times 10^{-14}$ for a 1-s averaging time (filled circles in Fig. 2). With the noise cancellation activated, the measured instability (filled triangles in Fig. 2) is reduced to $<9\times 10^{-15}$ for a 1-s averaging time and reaches 1 part in 10^{15} at 100 s, just slightly above the noise floor of the measurement system (open squares). The stability of transfer with noise cancellation, which is measured with independent detectors outside the stabilization loop, confirms that the photodetectors do not contribute any significant instability above the level of the noise floor.

Figure 2 also shows the stability for transmission through a 4.5-km laboratory-based network that comprises DSF, which yields pulses shorter than 40 ps. The instability without active noise cancellation is $>6\times 10^{-14}$ for a 1-s averaging time (bow ties in Fig. 2). Noise cancellation reduces it by an order of magnitude to $<7\times 10^{-15}$ for a 1-s averaging time, reaching a few parts in 10^{16} at 100 s (filled diamonds in Fig. 2).

For frequency-domain applications, such as remote comparisons of frequency standards, it is sufficient to reduce the long-term ($\geqslant$1-s) transfer instability as described above. However, for time-domain experiments that are sensitive to noise that occurs on faster time scales, it is necessary to consider the timing jit-

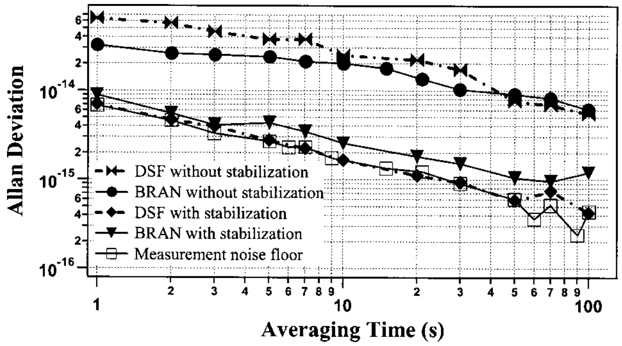

Fig. 2. Allan deviation for transfer of the 8th harmonic (774 MHz) of the laser repetition frequency over the BRAN and the DSF with and without stabilization. The measurement noise floor is determined by replacing the fiber link with ~1 m of fiber.

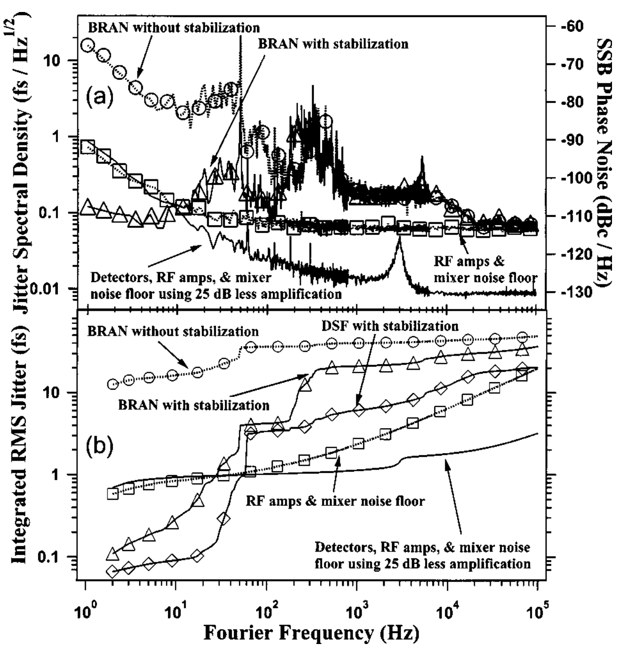

Fig. 3. (a) Jitter spectral density (left axis) and single-sideband phase noise (right axis) for transfer of the 81st harmonic (7.84 GHz) of a laser repetition frequency through the BRAN. Also shown are jitter spectra for the measurement system, revealing that the dominant phase-noise contribution is from the rf amplifiers. (b) Integrated rms jitter for transfer through the BRAN, transfer over the DSF, and measurement noise floor with and without reduction of the amplification.

ter introduced over a broad bandwidth. Figure 3(a) shows the jitter spectral density (left axis) and the corresponding single-sideband phase noise (right axis) for transfer of the 81st harmonic (7.84 GHz) of the laser repetition frequency through the BRAN fiber, preceded by the DCF. Without stabilization, the jitter rolls off at $\sim$8 kHz with a slope of ~ -10 dB/decade, until it hits the measurement noise floor near 20 kHz. Figure 3(b) shows that the integrated rms jitter over a bandwidth from 1 Hz to 100 kHz is reduced from $\sim$49 to $\sim$37 fs with the activation of the fiber-noise cancellation.

Figure 3(a) also shows the jitter spectrum for just the rf amplifiers and mixer used in the measurement system as well as for the jitter of the photodetectors in combination with the rf amplifiers and mixer using 25 dB less amplification. The noise floor of the measurement system is dominated by rf amplifier noise. The reduction of the gain reduces the integrated jitter [Fig. 3(b)] from $\sim$20 to $\sim$3 fs (over the full measurement bandwidth from 1 Hz to 100 kHz). As the jitter over the BRAN is not suppressed below the measurement noise floor with the active noise cancellation, the residual jitter measured in-loop is identical to what would be measured with a pair of out-of-loop detectors.

The noise cancellation is also used to reduce the jitter from transmission through the 4.5-km DSF. Because of the lower optical loss of the DSF and the accompanying enhanced rf signal strength, the lower noise-floor measurement setup involving 25 dB less amplification is used. With the noise cancellation, the rms jitter [Fig. 3(b)], integrated from 1 Hz to 100 kHz, is reduced to $\sim$20 fs. For timing distribution throughout a linear accelerator facility, only approximately a tenth of the length of the DSF used in our measurements would be needed. Therefore we expect that timing transfer exhibiting a jitter of only a few femtoseconds could be achieved with the application of this stabilization technique.

Active noise cancellation for the transfer of a rf signal over a fiber network has reduced the timing-transfer jitter, integrated over a bandwidth from 1 Hz to 100 kHz, to 37 fs for a 6.9-km round-trip installed fiber network and to 20 fs for a 4.5-km laboratory-based network. To our knowledge, these numbers represent the lowest reported amount of jitter for transfer of a timing signal over kilometer-scale distances by use of installed and laboratory-based optical-fiber networks. For future improvement, we plan to implement all-optical detection of the jitter to eliminate noise from rf amplifiers, which currently limits the noise floor of the measurement system.

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