Optical frequency transmission over 251 km of fiber with 6×10^{-19} residual frequency instability in 100 s

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Abstract: We demonstrate transmission of narrow-linewidth cw laser light (1535 nm) from a cavity-stabilized fiber laser over 251 km of single-mode optical fiber (76 km installed and 175 km on spools). Using standard Doppler-cancellation techniques, we transmit the light with a residual frequency instability of only 3×10^{-16} at 1 s averaging time and better than 6×10^{-19} at 100 s. This paper gives the practical experimental details that enabled this record distance and instability result. We find our ability to transmit over increased distances is limited by the transit time of the fiber and the environmentally induced fiber phase noise.

High stability optical atomic clocks operate with impressive fractional frequency instabilities expected to approach 10^{-18} upon future improvments[1-2]. If the frequencies from such clocks located remotely from each other are to be compared, there needs be an ultra-stable way to transport the frequencies between them. Accordingly, there has recently been an effort to demonstrate the transport of stable, coherent signals across fiber-optic networks for the purpose of comparing remotely located atomic clocks[3-5]. The practical problem is how to distribute these frequencies without significantly degrading their stability. Stable frequency can be distributed in the form of an RF modulation on an optical carrier[2, 5], and even higher stabilities can be obtained with a cw optical signal whose carrier frequency itself is the reference[4,6-7]. The difficulty in distributing highly frequency-stable light over optical fiber is that mechanical vibrations and thermal variations produce fluctuations of the fiber, causing Doppler shifts of the transmitted frequency. The impact of these effects can be dramatic. For example, a slow temperature increase of 5 °C over 12 hours causes an optical fiber to grow at a rate of 3 μm/(hr·m). In a 10 km fiber, this Doppler-shifts the transmitted frequency by 3 parts in 10^{14} (6 Hz for 1535 nm light). Such temperature variations and much higher-bandwidth random mechanical perturbations can be routinely expected along a fiber transmission path. Without mitigation, these perturbations severely limit the possibility to transmit very stable frequencies over optical fiber. However, these fiber phase fluctuations can be compensated by active feedback.

Here, we demonstrate stable optical frequency transfer over a 251 km fiber link stabilized by an optical feedback[6]. The experimental setup is shown in Figure 1. The design is based on two interferometers – the "local" interferometer is located with the laser source and beats the round-trip light (reflected from the distal end of the fiber link) with the source light to measure phase noise on the link and drive a compensating frequency shift of the source. The "remote" interferometer is at the distal end of the 251 km fiber link and beats the transmitted "one-way" light with the laser source to measures the transmitted frequency stability. Our link is in a loop geometry to enable characterization at the output. Thus light at the "remote" end emerges only a few centimeters from the "local" (input) end. Care was taken in assembly to prevent optical cross-talk between the "one-way" and "round-trip" light–optical isolation was measured at ~ 96 dB. The laser source is a cavity-stabilized fiber laser (CSFL) with a ~1 Hz linewidth and a drift rate of less than 1 Hz/s. The light exits the CSFL and travels approximately 10 m through an unstabilized fiber to a collimator launching the light into free space. About 8 % of the light is split off to be used as the local oscillator for the “remote” detector, and an additional 50 % goes to the “local” detector. The remainder of the light (about 4 mW) is launched into the fiber link. The link consists of a total 251 km of single-mode fiber, 76 km of which is installed in a loop around the city of Boulder, Colorado (known as the Boulder Research and Administration Network – BRAN). The other 175 km of fiber is wound on spools in the laboratory where the measurements took place.

Due to total link losses of about 62 dB, 4 bidirectional (no isolators) erbium-doped fiber amplifiers (EDFAs) were interspersed in the link. Care was taken in the placement of the EDFAs in order to ensure that the optical power level remained below the stimulated Brillouin scattering threshold throughout the link. The 251 km fiber channel was not ideal in that it contained at least 40 fiber connectors, most flat-faced (“PC” type), which generated reflections along the length. In particular, the 76 km installed portion of the loop was made up of 10-12 shorter sections all joined by PC connectors. The presence of these reflections throughout and the absence of isolators on the EDFAs placed a limit on the gain of any individual EDFA, to prevent lasing. The gains of the EDFAs used ranged from 7 dB to 25 dB. In the middle of the link an optical bandpass filter (~ 1 nm FWHM) centered at 1535 nm was used to reduce the accumulated amplified spontaneous emission power from the EDFAs.

Before entering the link, the light passes an acousto-optic modulator (AOM1) that adds a nominally 80.5 MHz frequency shift to the light. At the far end of the fiber link, AOM2 adds a 24 MHz shift. AOM1 is used as the means to apply the compensating frequency shift, while AOM2 serves to distinguish the light reflecting from the 50 % Faraday mirror (FM) at the far end of the link. Without AOM2, light from the connector reflections could cause the locking circuit to control the noise of only a reduced length of fiber.

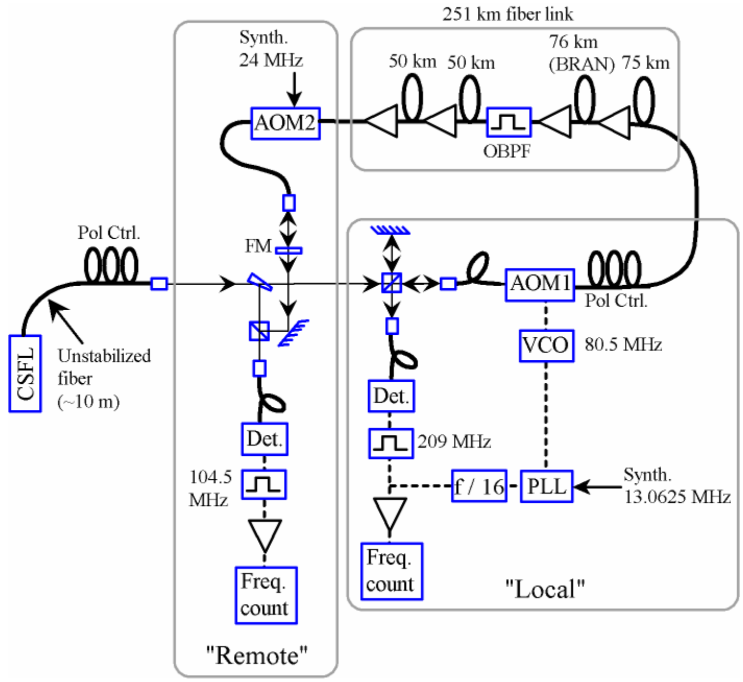

Figure 1. Experimental setup for frequency transfer and fiber stabilization. AOM, acousto-optic modulator; CSFL, cavity stabilized fiber laser; Det, detector, FM, Faraday mirror; OBPF, optical bandpass filter; PLL, phase-locked loop; Pol Ctrl, fiber optic polarization controller; VCO, voltage controlled oscillator. Thick lines are optical fiber, thin lines are free space propagation, dashed lines are electrical paths.

The light that passes through the Faraday mirror is mixed with the launched light (local oscillator) and is incident on a 125 MHz bandwidth photoreceiver (“remote” end). This “one-way” light beats with the unshifted light to create a 104.5 MHz (80.5 + 24) signal whose frequency is counted to determine transmitted stability. To ensure the stability of our RF measurement equipment, everything is synchronized to a 10 MHz frequency reference tied to the NIST Hydrogen maser. Light that reflects from the Faraday mirror travels back along the 251 km fiber and mixes with the local oscillator light to create a 209 MHz beat note on a 1 GHz bandwidth photoreceiver ("local" end). This 209 MHz signal is divided down by a factor of 16 to track phase noise fluctuations greater than π. The resulting 13.0625 MHz signal is fed into a phase-lock loop (PLL) control circuit, where it is locked to a low-phase-noise frequency generator. The feedback from the PLL drives a voltage-controlled oscillator (VCO), which in turn provides the RF signal into AOM1. The PLL controls the frequency shift of AOM1 in order to lock the round-trip optical frequency to the launched frequency, stabilizing the one-way light as well.

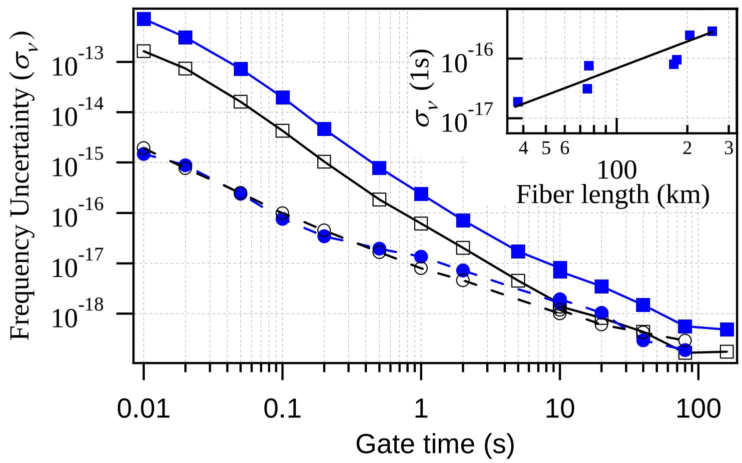

Figure 2. Residual frequency uncertainty for one-way (solid squares) and round-trip (open squares) signals over 251 km of stabilized optical fiber link (solid line); and a ~ 5 m link (circles and dashed lines). Inset: Measured (solid squares) and predicted (line) dependence of the uncertainty at 1 second versus fiber link length (from 40 km to 251 km).

With the system locked, we counted the frequency of both the one-way signal and the round-trip reference for the 251 km link and for the "shorted" case, where the link was replaced by about 5 m of fiber (no EDFAs). The resulting residual Allan deviation is shown in Figure 2. For gate times τ below 10 s, the residual Allan deviation is calculated directly from the frequency-counting result at the specified gate time. For τ > 10 s, the counter ran with a 10 s gate time, and a modified Allan deviation calculation[8] was used to extrapolate the results. For the 251 km link, the residual Allan frequency deviation for the one-way transmitted light goes as $1/\tau^{1.7}$, which nominally agrees with the $1/\tau^{1.5}$ dependence predicted for white phase noise on the fiber channel[8]. For comparison, we also measured the residual Allan deviations on the 251 km link with the system unlocked. At a 1 s gate time, the one-way unlocked Allan deviation was 1.3×10^{-13}, demonstrating a 26 dB improvement with locking.

This technique works best when the one-way and round-trip light see exactly the same noise processes, differing only by the obvious factor of 2 in intensity. Practically, this puts two requirements on the measurement system. First, it expects that the noise processes are reciprocal. That is, light traveling one direction in the fiber sees a total noise spectrum that is equal to that for light traveling in the other direction. A possible non-reciprocal process could be the presence of polarization-mode dispersion (PMD) in the fiber. Some researchers have noted an anomalous bump in the residual Allan deviation of the one-way light at long measurement times and have attributed this bump to asymmetric fiber behavior due to PMD in the link[5]. We have observed no such bump in our results and they do not appear to be PMD-limited. A second nonreciprocal process is due to optical paths that are "out of loop". This is the case when the "one-way" light physically travels a different portion of the path from the "round-trip" light. As seen in Figure 1, we worked to minimize these out-of-loop paths as well as the differing paths taken by the local oscillator light. However, even with the very short out-of-loop paths (a few centimeters of difference), we see ~ 7 dB difference in frequency uncertainty between the one-way and round-trip light. We also found significant improvement in the locked frequency stability when the interferometers were covered with a housing that isolated them from air currents. For only 5 m of fiber in the link, we measured a frequency standard deviation of 1.5 mHz (1 s gate time); when we removed the cover on the interferometers, the standard deviation went up to 12 mHz.

We experimented with several fiber lengths ranging from 40 km to 251 km (various combinations of installed and spooled fiber). The 1 s residual Allan deviations are plotted in the inset of Figure 2. As the length of the fiber channel increased, several practical aspects inhibited our ability to stabilize the fiber and had to be overcome. Fiber attenuation with length reduces signal power (overcome via the EDFAs) and reduces signal to noise ratio (not a length-limiting effect for loop lengths below 10^7 km)[9]. Greater fiber lengths also increased the drift rate of the state of polarization (SOP) in the fiber link. This was most problematic for the round-trip signal, where changes in SOP reduced the overlap with the local oscillator light, degrading the SNR of the RF beat note. Since AOM1 was locked to this signal, SOP drift limited the ability to maintain long-term lock. This was mitigated by using the Faraday mirror at the end of the fiber path, which maintained the SOP of the round-trip at the detector regardless of polarization changes in the transmission path. The Faraday mirror does not stabilize the SOP of the one-way light. The most difficult limit was imposed by the ~ 2.6 ms round-trip transit time of the 251 km fiber span. This limited the control bandwidth of the locking circuit to below 210 Hz (1/(2 *2.6 ms)). This bandwidth limitation is our current limit preventing longer link lengths.

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