Optical frequency transfer over 38 km of installed fiber at less than 3×10^{-19} residual fractional instability

P. A. Williams, W. C. Swann, and N. R. Newbury
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305
Tel: (303) 497-3805, Fax: (303) 497 -3387, E-Mail: pwilliams@boulder.nist.gov

Abstract: We transmit a narrow-linewidth cw laser at 1535 nm across 38 km of installed fiber. Through standard Doppler-cancellation techniques, we achieve a residual fractional frequency instability of $4\text{x}10^{-17}$ at 1 second averaging time.

Traditionally, the transfer of stable frequencies over long distances has been accomplished by the use of satellite-based systems. Fiber optic networks provide a promising alternative means of distributing stable frequencies. The frequencies can be transmitted either in the rf-domain as a modulation of the optical carrier, or directly as the frequency of the optical carrier itself.[1-5] The latter method of frequency transfer is appropriate for applications where the highest frequency stability is needed or where an optical signal is needed at the end site. Recently, fractional frequency stabilities of 6×10^{-17} in 1 second were demonstrated in an in-house ¾ km long coherent fiber network that incorporated three different Doppler cancelled fiber-links carrying stabilized cw light and two remote frequency combs to permit coherent transfer of the optical signals to other wavelengths, or potentially to the microwave domain.[6] Here we demonstrate the low-instability transfer of optical frequencies over a much longer 38 km installed fiber link. We measure a relative fractional frequency stability of 4×10^{-17} at 1 s, which averages down to $< 3\times10^{-19}$ in 10^4 s.

The stability of long-distance optical frequency transport over fiber is seriously limited by Doppler shifts from fiber length fluctuations. These fluctuations can be sensed by reflecting the signal back to the source and corrected by applying a compensating frequency shift to the transmitted light.[7,8] This approach requires a source coherence length greater than the round-trip distance. Here we use a cavity-stabilized fiber laser (CSFL) at 1535 nm with ~1 Hz linewidth and drift rate < 1 Hz/s.

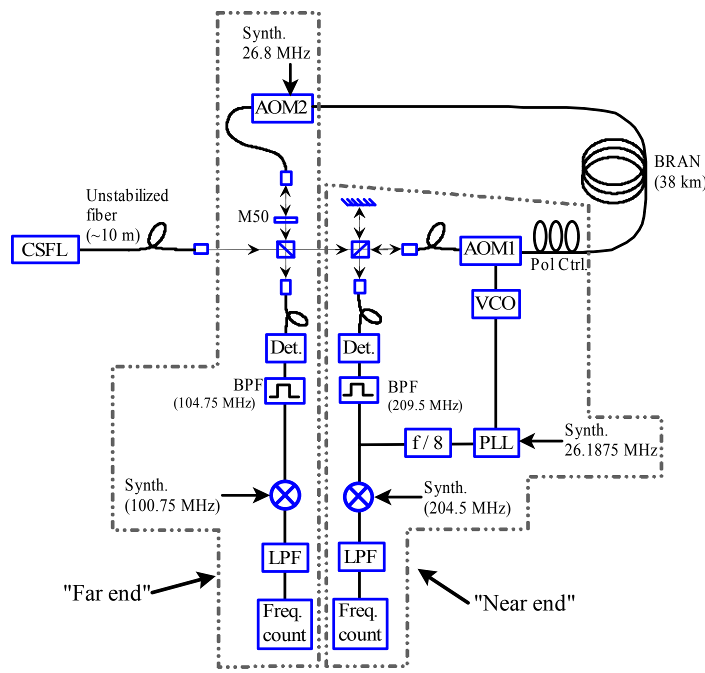

Fig. 1 Experimental setup. AOM, acousto-optic modulator; BPF, bandpass filter; BRAN, 38 km installed fiber loop; CSFL, cavity-stabilized fiber laser; Det., detector; f/8, 8x frequency divider; LPF, low-pass filter; M50, 50 % reflecting mirror; PLL, phase-lock loop; Synth., frequency synthesizer; VCO, voltage-controlled oscillator.

As shown in Figure 1, light from the CSFL is launched into an installed loop of 38 km of single-mode fiber which traverses the city of Boulder and is referred to as the Boulder Research and Administration Network (BRAN). A shorter portion (~7 km) of this network was used in some of the original fiber cancellation work.[5] This 38 km fiber forms a loop and we have access to both ends of the fiber in our laboratory. Our experiment was set up in such a way that light traveling the 38 km ("one-way") is detected by the "far-end" detector. Light reflected back from the "far end" travels a 76 km round-trip path and is detected by the "near-end" detector. To enable frequency comparison, both the "near-end" and "far-end" detectors are on the same optical bench. The near-end acousto-optic modulator (AOM1) at the BRAN fiber input acts to compensate for phase noise seen in the round-trip light. At the far end, AOM2 enables the system to distinguish stray reflections from light that has traveled the full 38 km to the fiber end and reflected back. The 76 km round-trip beat signal and the 38 km one-way beat signal are filtered and counted.

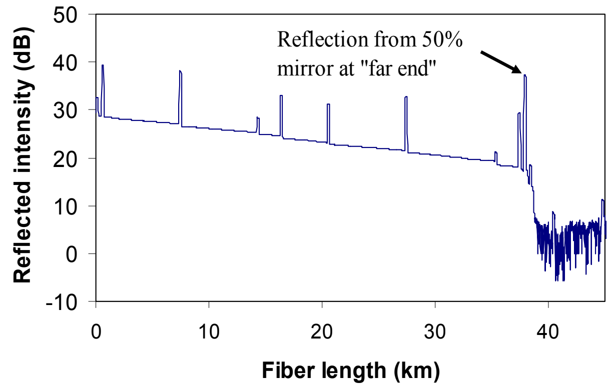

Fig. 2 Optical Time Domain Reflectometry (OTDR) trace for the 38 km long BRAN fiber: end-to-end loss 8.3 dB (0.2 dB/km). Reflected intensity spikes indicate locations where the fiber comes above ground to a patch panel.

Figure 3 shows the Allan deviation (fractional frequency instability) from a 15-hour run. The one-way and round-trip light have essentially the same values. At a 1 s averaging time, the fractional frequency stability is 4×10^{-17}. If Doppler cancellation is disabled, this number becomes 5×10^{-14}. A curve fit to the one-way data yields a $1/\tau^{0.6}$ dependence of the Allan deviation on the averaging time τ. The average difference in frequency between the launched CSFL source and that detected at the "far end" was 10 μHz (a fractional frequency error of 5×10^{-20}). Some researchers have noted an anomalous bump in the Allan deviation of the one-way light at long measurement times and have attributed it to asymmetric fiber behavior due to Polarization-Mode Dispersion (PMD) in the fiber.[9] We did not observe this bump in our measurement. We measured the Differential Group Delay of the fiber to be 0.13 ps (averaged over 1480-1570 nm). This is much smaller than the 7 ps of reference 9 and could explain the lack of PMD effects.

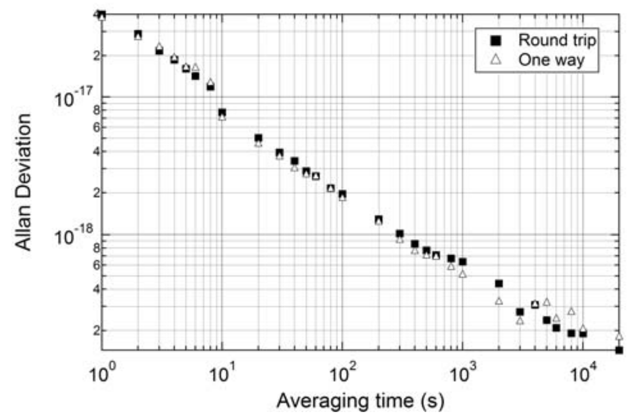

Fig. 3 Allan deviation (fractional frequency instability) measured for 1535 nm cw laser. The "one-way" signal was measured at the far end of 38 km of installed fiber, the "round-trip" signal was reflected by the far-end mirror and measured at the near end (76 km total travel).

1 S. M. Foreman, K. W. Holman, D. D. Hudson, et al., Rev. Sci. Instrum. **78**, 021101 (2007).
2 F. Narbonneau, M. Lours, S. Bize, et al., Rev. Sci. Instrum. **77**, 064701 (2006).
3 C. Daussy, O. L. O, A. Amy-Klein, et al., Phys. Rev. Lett. **94**, 203904 (2005).
4 K. W. Holman, D. D. Hudson, J. Ye, et al., Opt. Lett. **30**, 1225 (2005).
5 J. Ye, J.-L. Peng, R. J. Jones, et al., J. Opt. Soc. Am. B **20**, 1459 (2003).
6 I. Coddington, W. C. Swann, L. Lorini, et al., Nature Photonics, submitted (2007).
7 B. C. Young, F. C. Cruz, W. M. Itano, et al., in *Laser Spectroscopy (XIV International Conference)*, edited by R. Blatt, J. Eschner, D. Leibfried and F. Schmidt-Kaler (World Scientific, Singapore, 1999), p. 61.
8 L. S. Ma, P. Jungner, J. Ye, et al., Opt. Lett. **19**, 1777 (1994).
9 O. Lopez, C. Daussy, A. Amy-Klein, et al., in *2006 IEEE International Frequency Control Symposium and Exposition* (IEEE, Miami, Florida, 2006), p. 80.