Practical performance limits on optical frequency transfer over fiber optic links

P.A. Williams, W.C. Swann, and N.R. Newbury
National Institute of Standards and Technology, 325 Broadway, Boulder, CO, USA, 80305
pwilliam@boulder.nist.gov

Abstract: We present theory and experiment quantifying the limitations to stable transport of optical frequencies over optical fiber. These are fundamental fiber noise, propagation delay, bidirectional propagation and system noise in the measurement interferometers.
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1. Introduction

Stable transport of RF or optical reference frequencies over optical fiber has applications for comparisons of optical clocks, searches for variations in the fundamental constants, radio astronomy, particle physics and broad baseline interferometry.[1,2] We previously demonstrated transmission of a narrow 1535 nm stabilized laser light over 251 km with a fractional frequency instability of 6×10^{-19} in 100 s [3,4] and here use the same measurement system to quantify the effects limiting the stability of optical frequency transfer.

Our measurement system is described in detail in [4] but is summarized here as well. The stabilized optical frequency source is a 1535-nm cw fiber laser with a 1-Hz linewidth (coherence length ~3×10^{8} m) phase-locked to a stabilized optical cavity via the Pound-Drever-Hall technique.[5] The light is transmitted from the local end through an acousto-optic modulator (AOM) and the optical fiber link (ranging from 0 to 251 km) to the remote end (circled back to the same optical table as the local end) where the frequency stability and phase noise are measured with an interferometer which mixes the transmitted light with reference light from the source. To enable stabilization of the transmission link against thermal drifts and acoustic vibration we use a standard Doppler cancellation technique [6,7] which works as follows. At the remote end, a partial reflector sends ~50 % of the light back through the link to the local end where it is mixed with reference laser light. The resulting beat note is fed to a phase-locked loop (PLL) used to control the offset frequency of the AOM thus cancelling frequency noise on the round-trip laser light (within the control bandwidth of the PLL). Assuming correlated noise on the outbound and return light, the remote light will be parasitically stabilized along with the local (round-trip) light. Using this system, we examined performance-limiting factors for optical frequency transmission.

2. Installed network configuration (bidirectional fiber propagation)

The Doppler cancellation technique relies on outbound and round-trip light traveling in the same optical fiber in order to maximize correlation between the one-way and round trip noise sources. However, typical installed long-haul networks have regularly-spaced erbium doped fiber amplifiers (EDFA) at 30-100 km intervals. The EDFAs are usually equipped with optical isolators preventing bidirectional propagation in the transmission fiber, which would block the reference signal for the Doppler cancellation scheme. We investigated a simple solution by sending the reference signal back to the local end through a different fiber. We used a duplexed fiber where the two fibers are part of the same cable but with the outgoing and return fiber separated by < 2 mm. We tested performance on two lengths of duplexed fibers, 400 m (spooled) and 38 km (installed) and compared the results to a true bidirectional system where the reference signal was retroreflected back through the same fiber.

Figure 1a shows the setup with optical circulators directing outbound and return light to different fibers in the duplexed pair. Above 30 Hz, we find the one-way phase noise is controlled to a level close to the theoretical limit. At lower frequencies f, there is still some suppression of the fiber noise, but the one-way phase noise begins to diverge as $1/f$. Figure 1b gives the delivered frequency offset (with one-hour running average) for the 38 km link in both bidirectional and duplexed configurations. In the 38 km duplexed fiber, the averaged frequency error reaches ~0.7 Hz with a ~24 hour period. Figure 1c shows the measured Allan deviation for both link lengths. In both duplexed cases, we observe the characteristic flat dependence on gate time as a result of the flicker phase noise. In contrast, the true bidirectional noise cancellation continues to average down with gate time. Since the flicker phase noise is not affected by the phase lock, we expect it to scale linearly with fiber length (Allan deviation will scale as the square root of length). This result can be compared to those of Daussy *et al.* where the phase noise between RF modulated light propagating in two installed adjacent fibers (48 km) was found to be a factor of 10 lower than the noise in a single fiber. Despite this correlation, we conclude that long-range fiber-optic transfer of frequencies is likely not competitive with satellite-based techniques unless a true bidirectional fiber transport is possible.

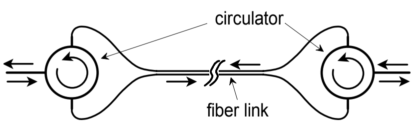

Fig. 1a. Experimental setup to replace bidirectional fiber link with duplexed fiber and a pair of circulators.

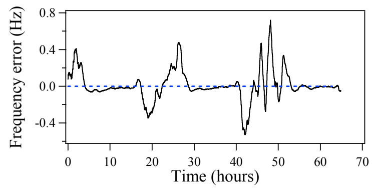

Fig. 1b. Counted frequency error (difference from transmitted frequency) for 38 km link in bidirectional (dashed) and duplexed (solid) configuration.

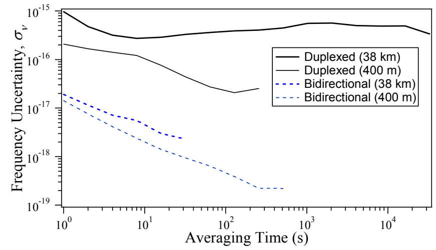

Fig. 1c. Allan deviation for duplexed and bidirectional fiber configurations of 38 km (installed) and 400 m (spooled).

3. Noise sources

The dominant noise source in bidirectional transfer is due to the uncompensated phase noise in the fiber link itself. Laser source noise is negligible as long as the variations in the stabilizing cavity's length are far less than the variations in the uncontrolled fiber link. Noise in the RF electronics is negligible for an easily achievable RF frequency instability of 10^{-12}. However, we find that even for perfect noise cancellation of the round-trip light, the one-way light will still suffer from some residual fiber-induced phase noise due to the length-dependent delay between the application of compensation at the local AOM and the emergence of light at the remote end. For an uncompensated uniformly distributed fiber phase noise $S_{fiber}(f)$ the minimum phase noise achievable by Doppler frequency compensation is $S_{Locked}(f) \approx (1/3)(2\pi f\tau)^2 S_{fiber}(f)$,for low Fourier frequencies, f. This means optimum frequency transmission is predictable from the uncompensated fiber noise. Figure 2a shows measured phase noise for different link lengths, and figure 2b shows the integrated noise vs. link length compared to the theory. Furthermore, we find that the uncompensated phase noise on installed optical fiber can be ~20 dB larger than for equivalent lengths of spooled fiber, suggesting that laboratory demonstrations of transmission performance are best done using installed fiber as the test link. This uncompensated phase noise will limit the Allan deviation for intermediate gate times. For long gate times, the Allan deviation will be limited by uncompensated Doppler shifts within the interferometer itself.

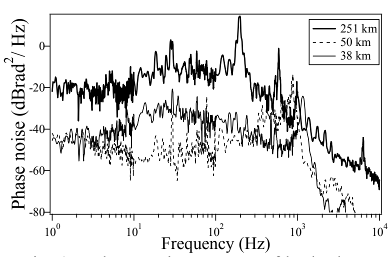

Fig. 2a. Phase noise spectra of locked one-way transmission at various link lengths.

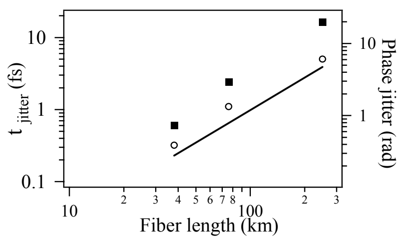

Fig. 2b. Integrated jitter: total timing jitter (squares), jitter without servo bump contribution (circles), theoretical prediction from integrating S_{Locked} (line).

4. References

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