Optical Frequency Transfer Stability of 1E-15 at 1 Second Over Correlated Core Pairs in a 40 km 7-core Fiber Link

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Abstract: We demonstrate a 40km stabilized optical frequency transfer system with fractional frequency stability of 1e-15 at 1s without single-core bidirectional propagation. Highly correlated cores of a 7-core fiber are used for signal transmission and return, mitigating uncorrelated phase fluctuations found in duplex approaches. © 2022 The Author(s)

1. Introduction

Multicore fibers (MCFs) are of interest as a potential solution in multiple applications, including high capacity fiber transmission [1], distributed sensing [2], and recently for precision optical clock [3] and quantum-state [4] distribution and synchronization. In particular, the latter two applications leverage the high relative phase stability between cores of an MCF which arises from the co-location of the cores in a shared cladding. Another application that can leverage precision phase stability is stable optical frequency distribution. Currently, stable distribution of such sources is crucial to a wide range of research fields such as fundamental physics, radio astronomy, and particle physics, since cost, space, and technical requirements makes on-site generation impractical. Frequency transfer over stabilized single mode fiber spans is currently the only method with the required precision to be compatible with the most stable sources currently in use [5], and can make use of already-deployed fiber networks. This method requires the transmitted optical signal to be returned to the source to detect and compensate for fiber path length fluctuations and requires the single fiber span to support bidirectional propagation to ensure that phase fluctuations in the transmission and return path are well correlated. However, bidirectional operation has several issues – careful design is required to minimize noise added by Rayleigh scattering which can significantly increase system complexity, and many currently deployed fiber networks employ isolators before and after amplifier stages and therefore do not allow for bidirectional propagation on single fiber cores. Furthermore, use of duplex fiber pairs to avoid bidirectional propagation have demonstrated that performance penalties caused by uncorrelated phase drift in the transmission and return paths are too large to make this method feasible [6]. Therefore, MCF presents an attractive option for stable frequency transfer systems that do not employ bidirectional propagation, and instead return the compensation signal on a separate, but highly phase-correlated fiber core.

In this paper we demonstrate stable transmission, stability of 1E-15 @ 1s, of a Hz-linewidth stable reference laser (SRL) over 40 km of spooled 7-core uncoupled multicore fiber, using a single pair of separate cores for transmission and return signals. Frequency noise measurements of the transferred signal system show that accurate link stabilization using a separate signal return core can be achieved even in environment with large amounts of acoustic noise and vibrations. Finally, we quantify the degree of phase correlation, and thus performance of the link, as the variation between core pairs likely as a result of bending strain caused by the fiber spooling.

2. Results

2.1 Stabilization Scheme

The stabilized span can be divided into the local region, containing the source laser (ECDL locked to a high-finesse vacuum cavity) and all stabilization equipment, the fiber span, in this case a 40 km 7-core multicore fiber (figure 1(b)) with spliced fanouts on each end, and the remote end, where the stable optical frequency is to be delivered. To ease evaluation of the system, this experiment used a single spool of 7-core fiber, acoustically insulated and placed on an active isolation table to reduce strong coupling to ambient vibrations. In addition, all three sections were located on the same optical table to allow direct measurement of the delivered optical frequency. As shown in figure 1(a), the stabilization scheme requires the use of one of two core-pairs that exhibit highly correlated phase noise properties. Light from the stabilized laser is frequency shifted by an acousto-optic modulator (AOM) before being transmitted from the local side to the remote side of the fiber span on one fiber core (core 1). On the remote side of the span, part of the transmitted power is directed back to the local side on the other core pair (core 6), where it passes through a second AOM driven by the same frequency source. Span-induced phase noise is measured by detecting the beat between the stable laser and light returning from the remote side of the span and comparing the

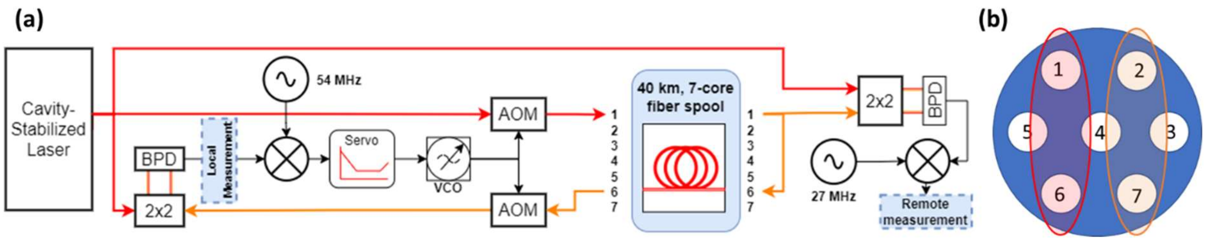

Figure 1 (a) Stabilized optical frequency transfer setup. (b) 7-core multicore fiber cross section. Core pairs with highly correlated phase noise (cores 1+6 and 2+7) are highlighted in red and orange, respectively.

phase fluctuations of this beat note relative to a stable radio-frequency source. Phase fluctuations can then be compensated by applying feedback to the driving frequency of the AOMs so that the measured beat note is phase-locked to the RF reference frequency. Since the transmission and return path are not identical, as would be the case when using single core bidirectional propagation, the compensation scheme will only correctly suppress fiber phase noise that is highly correlated between both cores. Finally, relative frequency noise between the stable laser source, the delivered optical frequency on the remote side, and the returned optical frequency for compensation were measured simultaneously by sampling their respective beat notes on a high-speed digital-to-analog converter with a large memory depth.

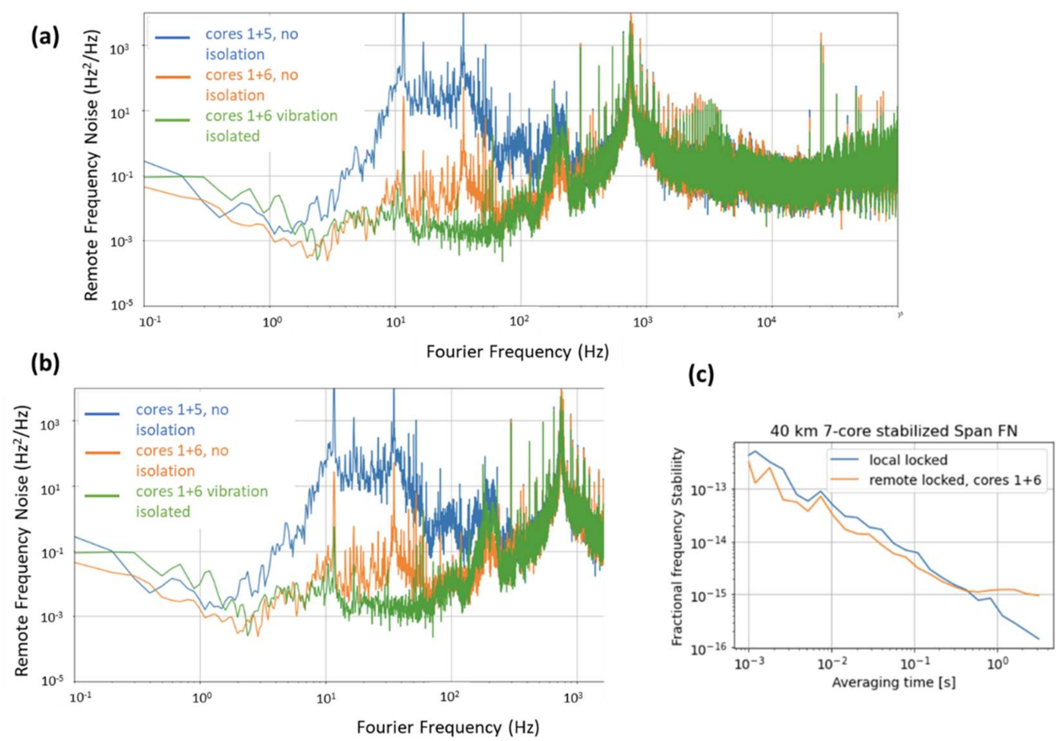

Figure 2 (a) Frequency noise results for the 40 km stabilized link with vibration isolation table engaged. Residual locking error measured on the local side in blue, remote side frequency noise of correlated cores (1+6) in orange, and frequency noise of less correlated cores (1+5) in green. (b) Comparison between locked remote side frequency noise with and without vibration isolation of the 40 km spool. (c) Overlapping Allan deviation of local and remote sides of the link.

2.1 Stabilized Span Performance

As shown in figure 2, the relative frequency between the source laser and delivered optical frequency was measured with (figure 2(a)) and without (figure 2(b)) an active vibration isolation table activated to suppress building vibrations that couple strongly to the spooled fiber. In each case, the result is compared to the in-loop error generated by the beat between the round-trip signal and the source laser. In each case, results were compared when using two highly correlated fiber cores (1 and 6) to using two cores with substantially less correlation (cores 1 and 5). From figure 2(a), it is apparent that use of correlated cores allows for precise compensation of noise at frequencies greater than

~ 10 Hz, with some slightly reduced performance at lower frequencies. Furthermore, comparison of performance without active vibration isolation for the fiber spool (fig. 2(b)), shows that highly correlated cores reject disturbances from low-frequency vibrations better than other core pairs -- by up to three orders of magnitude at some frequencies. The physical cause of these performance differences is the subject of future investigation. Other work measuring core-to-core phase stability [7] did not measure noise at these time scales, and at longer timescales did not report observation of significant differences in dynamic skew for different core pairs. Given the geometry of the fiber cores, bending strain introduced by spooling may act such that only core pairs under similar strain behave identically when perturbed.

3. Conclusion

We demonstrate optical frequency transfer with a fractional stability of 1E-15 @ 1s of a Hz-linewidth SRL over 40 km of spooled 7-core fiber, using separate cores for transmission and return signals. Frequency noise measurements of the transferred signal system show that accurate link stabilization using a separate signal return core can be achieved even in environment with large amounts of acoustic noise and vibrations. The degree of phase correlation between cores, a primary limitation, varies between core pairs, possibly as a result of bending strain in the spooled fiber.

4. References

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