One-Way Temperature Compensated Fiber Link

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***Abstract*— We will discuss our work on a one-way optical fiber frequency transfer system. The link removes thermally generated delays through sensing the difference in temperature dependent changes in the group index of the fiber for two wavelengths. The system monitors the phase difference between two amplitude-modulated lasers at the edges of the C-band. Using this signal, a temperature controlled spool of fiber compensates for thermally induced phase excursions in the link. We will present preliminary results as well as a discussion of performance limitations.**

I. Introduction

As atomic clock technology has progressed, great improvements in stability and accuracy have been achieved. Atomic fountain clocks have short-term stabilities in the upper 10^{-14}'s at one second and integrate down to the low 10^{-16}'s in a day [1]. Newer optical clocks are reaching short-term stabilities in the low 10^{-15}'s and averaging down into the 10^{-17}'s in an hour [2]. It is necessary to have a time and frequency transfer method capable of supporting this level of performance.

One of the standard ways of transmitting time and frequency is through two way satellite time and frequency transfer (TWSTFT). While it is practical for transmitting time and frequency over long distance, the performance is not acceptable for some of the newer high quality clocks. Currently, TWSTFT can transmit frequencies with instabilities at the 10^{-15} level and time at the 1ns level after a day of integration [3]. It is clear that to transfer stabilities achieved with modern atomic clocks, both microwave and optical, better transfer methods are needed.

One possibility is time and frequency transfer through fiber optic links. There are many promising aspects for using fiber optic links. First, there is an existing infrastructure that provides a large network for transferring time and frequency. The links are low loss over large distances and are well isolated. The access to a common return path allows for measurement and compensation of phase fluctuations. Finally, there is great potential for scalability in fiber optic networks.

Most methods for transferring time and frequency along fiber links involve establishing a two way link. The timing signal is sent down the link and then returned to the transmitting station. At the transmitting station, the phase variation brought about by fiber noise are measured and corrected for. One approach is to use an amplitude modulated signal. Short-term stabilities of 10^{-15} integrating down into the low 10^{-18}'s have been demonstrated [4]. Another approach involves using the phase of the optical carrier itself. Excellent performance has been achieved with short-term stabilities in the 10^{-16}'s averaging down to the 10^{-19}'s in a day [5]. An in depth overview of fiber transfer techniques can be found in [6].

Here we present results on a different type of fiber optic link. This is a one-way temperature compensated fiber link [7]. A one-way, amplitude modulated signal is transmitted along the fiber along with a proxy for measuring the temperature. The proxy signal is then used to compensate for temperature induced phase fluctuations along the link. This approach differs from the previous methods in that it is a one-way transfer. Bidirectional access to the fiber is not necessary as in the case of two-way links. Also, the ability to build simpler broadcast networks exists with improved scalability.

This one-way transfer method relies on measuring temperature indirectly. We use the phase difference between two separate colors propagating along the fiber to determine temperature. This is due to the temperature dependence of dispersion in fiber. All materials have an index of refraction for light and exhibit dispersion, meaning that the index is wavelength dependent. But in addition to being wavelength dependent, the index is also temperature dependent.

We can model the index of refraction for fiber by using the Sellmeier coefficients for fused silica [8]. In particular we can use temperature dependent coefficients to see the expected temperature dependent features. The temperature dependent index of refraction has the following form

$$n^2(\lambda,T) - 1 = \sum_{i=1}^{3} \frac{S_i(T)\cdot\lambda^2}{\lambda^2 - \lambda_i^2(T)} \qquad (1)$$

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14. ABSTRACT

We will discuss our work on a one-way optical fiber frequency transfer system. The link removes thermally generated delays through sensing the difference in temperature dependent changes in the group index of the fiber for two wavelengths. The system monitors the phase difference between two amplitude-modulated lasers at the edges of the C-band. Using this signal, a temperature controlled spool of fiber compensates for thermally induced phase excursions in the link. We will present preliminary results as well as a discussion of performance limitations.

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where

$$S_i(T) = \sum_{j=0}^{4} S_{ij} \cdot T^j \quad (2)$$

and

$$\lambda_i(T) = \sum_{j=0}^{4} \lambda_{ij} \cdot T^j. \quad (3)$$

The S_i coefficients are determined by the strength of resonance features that occur within the fiber at wavelengths λ_i. A thorough description of this model as well as the complete set of values for the different coefficients can be found [8].

Based on this model, we can calculate the time delay for a pulse or any amplitude modulation feature traveling down the fiber at a given wavelength and temperature. If we have two pulses at two different colors traveling down the fiber at a given temperature, they will arrive with a fixed time difference. As the temperature changes, that time difference changes based on the changing index of refraction. This is shown in Figure 1.

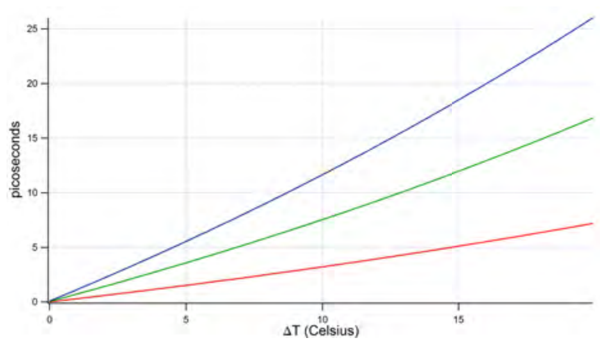

Figure 1. Temperature dependent phase shifts. Calculate results for the changing time delays between two pulses at different colors transmitted on 1km of single mode fiber as the temperature of the fiber changes. Blue corresponds to light at 1530nm and 1565nm. Grey is 1530nm and 1553nm. Red is 1530nm and 1540nm. Increasing wavelength separation gives increasing sensitivity to the temperature dependent phase shift.

From this we see that it is possible to derive a change in temperature in the fiber by measuring the change in time delay between two different color signals. We can use this indirect temperature measurement as a means of compensating for temperature induced phase changes in the fiber. Note that this method only compensates for temperature induced effects. It will not compensate for any mechanically induced phase fluctuations.

II. EXPERIMENT

As has been shown, it is possible to use the time delay between pulses at two different colors as a proxy for temperature measurements of a fiber link. Instead of measuring time delays between pulses, the phase change between two amplitude modulated signals were measured. The experimental setup to measure is described in the following and shown in Figure 2.

A master oscillator at 5MHz drives the system on the transmit side. For testing purposes this is just a high quality crystal oscillator. That 5MHz signal is multiplied up to 100MHz. The 100MHz signal feeds a phase locked dielectric resonant oscillator to produce a signal at 6.8GHz. This signal is split and used to modulate two transmit laser modules.

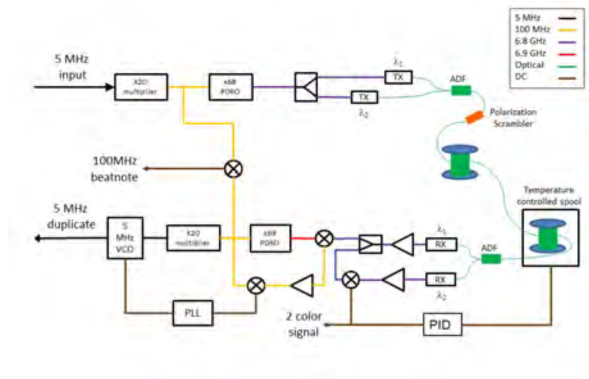

Figure 2. Experimental setup.

The transmit modules are laser diodes with electro-absorptive modulators operating at λ_1 = 1530nm and λ_2 = 1553nm. The two signals are combined onto one fiber using and add/drop filter. The signal then goes through a polarization scrambler. It was experimentally verified that the two color signal has a strong dependence on any birefringence due to residual stress in the fiber. By scrambling the polarization, the signal is averaged over all polarization states and that sensitivity is reduced.

At this point the laser signal travels down the link. For testing purposes, this link is a spool of fiber residing in an environmentally controlled chamber. It was possible to adjust the length of the link from 1m to 30km.

After passing along the link, the signal enters the receive station. The first stage of this station is a temperature controlled spool. The spool consists of 5km of bare single mode fiber wound on an aluminum mandrel. The spool is placed in an insulated box and is temperature controlled using a TEC and commercial temperature controller.

After the temperature controlled spool, the two wavelengths are separated using another add/drop filter and fed to two separate fiber coupled photo receivers. The outputs of each receiver are amplified with a high gain microwave amplifier. The 6.8GHz modulation signal at wavelength λ_1 is split with one half mixed with the entire signal at wavelength λ_2. The change in phase between the two colors' AM signals is the previously described two color signal. The two color signal is amplified and fed to a PI controller. The PI controller determines the set point for the temperature controlled spool to cancel temperature induced fluctuations in the fiber.

The second half of the signal at wavelength λ_1 is used to phase lock a high quality 5MHz quartz crystal to the transmitted signal. The 5MHz signal from the quartz crystal is multiplied up to 100MHZ and then fed to a phase locked DRO to produce 6.9GHz. The 6.8GHz signal is mixed with the 6.9GHz signal to create a 100MHz signal which is then mixed with the intermediate 100MHz signal in the send station. This error signal is then used to phase lock the crystal to the transmitted signal, completing the clock recovery at the receive station.

In order to test the stability of the transmitted signal, a portion of the 100MHz signal from the transmit station and the send station are mixed together. The resulting beat note is recorded with an analog to digital convert and later analyzed for stability.

III. RESULTS AND CONCLUSIONS

A first test was to measure the size of the two color signal as a function of temperature change. A 5km spool of fiber was used for the link. The environmental chamber cycled the temperature with 4°C linear ramps every two hours. The PI controller for the compensation spool was turned off, and the temperature set at a fixed value. The two color signal was recorded as was the 100MHz beat note between the transmit and receive stations.

Figure 3 show the results of the measurement. As can be seen, as the temperature changes, there is a change in the relative phase between the transmit and receive stations. For the given link length and temperature difference this is approximately 300ps. Likewise, a phase change in the two color signal is evident, although with a lower magnitude. For the same length and temperature change, the phase change is about 1ps. There is excellent correlation between the 100MHz beat note phase change and the two color signal phase change. The lever arm, or ratio of actual phase change to two color signal phase change, is about a factor of 300. This is an important value in that any noise on the two color signal will get multiplied by the lever arm and written on the actual signal.

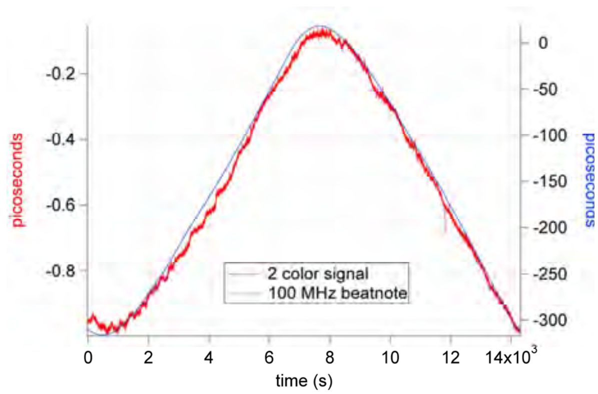

Figure 3. Lever arm measurement. The phase change for the two color signal (red) and the 100MHz beatnote (blue) as a function of changing temperature. The two color signal changes by approximatel 1ps while the 100MHz beatnote changes by over 300ps.

As a note, these results were achieved after ensuring similar fiber throughout the link. The scheme relies on a direct correspondence between temperature and expansion since the actual phase variations are not measured [9]. This means that the coefficient of thermal expansion must be constant for the entire link otherwise different temperature changes give rise to different phase variations. Therefore, bare single mode fiber was used throughout the experiment.

The next test was to use the temperature controlled spool to cancel out the temperature induced phase fluctuations and lock the link. The same 5km spool was used for the link and the same cycling conditions were used in the environmental chamber. The PI controller was turned on and used to adjust the temperature of the compensation spool. The net effect was to drive the two color signal to zero.

The results of locking the link are shown if Figure 4. The link was locked for approximately one day. The two color signal held constant near zero while there are small fluctuations on the 100MHz beat note. For comparison, the link was unlocked, denoted by the black vertical line in Figure 4, and allowed to run for about one day. It is clear that the two color signal as well as the 100MHz signal have much larger phase variations when unlocked.

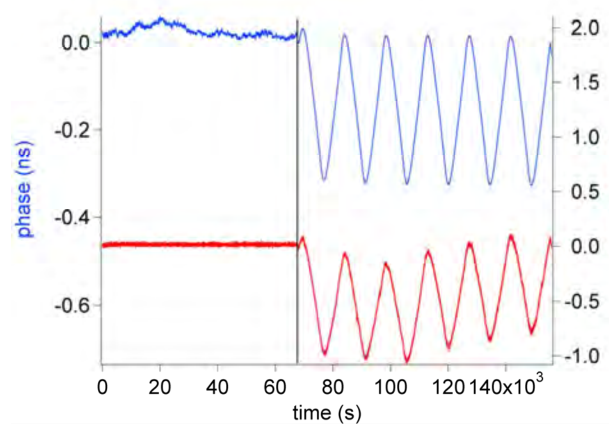

Figure 4. Locked and unlocked link performance. The plot in blue is the 100MHz beatnote signal and the plot in red is the two color signal. The first half of the data set corresponds to the link being locked and compensated. At the black line, the compensation is turned off.

Figure 5 shows the stability of the locked and unlocked links when the environmental chamber is cycling. The Allan deviation is plotted for both situations. First, consider the unlocked case. The stability starts of at 6×10^{-14} at 1 second. It integrates down as $1/\tau$ until about 100 seconds. At that point, the effects of temperature cycling become apparent causing the stability to increase as τ with a peak at half the cycling time of 2 hours.

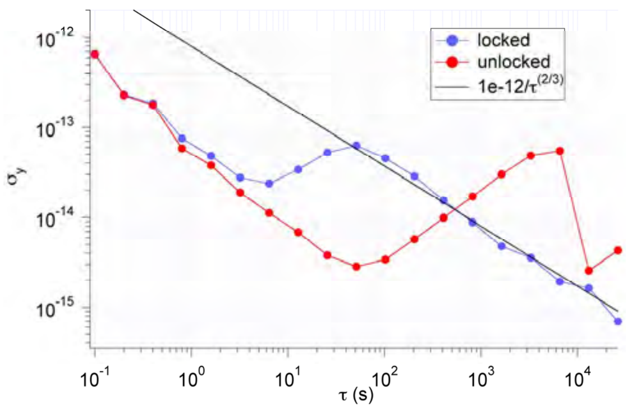

Figure 5. Link Stability. Plotted are the Allan deviations for the locked and unlocked data presented in Figure 4. A reference line of $10^{-12}/\tau^{2/3}$ is plotted as well.

In the case of the locked link, the effects of temperature cycling are removed. Initially, the stability is 6e-14/τ like the unlocked case. At around 10s the stability turns up and eventually latches on to a trend of $1\times10^{-12}/\tau^{2/3}$. This comes about because of the temperature control loop and the noise floor of the two color signal. The temperature controlled spool has a time constant on the order of 10 seconds hence the deviation from the unlocked loop around 10 seconds. The stability eventually rolls over to a line defined by the noise floor of the two color signal and the lever arm of the system. For a 10km length of fiber, the noise floor of the two color signal is ~ $3\times10^{-15}/\tau^{2/3}$. The measured lever arm is approximately 300; therefore the noise floor is multiplied up by 300 and added to the stability of the loop. That corresponds to ~$9\times10^{-13}/\tau^{2/3}$.

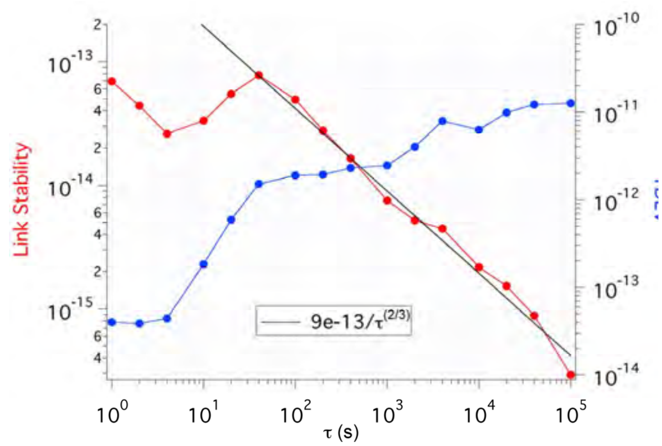

Figure 6. Extended link stability plot. Plotted are the Allan deviation and TDEV for a 5 day continual run of the locked link. . A reference line of $9\times10^{-13}/\tau^{2/3}$ is plotted as well.

The results of a longer run with the link locked for 5 days are shown in Figure 6. Throughout, the environmental chamber was changing the temperature as in Figures 3 and 4. From the Allan deviation, we see that the locked link integrates down to the mid 10^{-16}'s in one day with the phase fluctuations suppressed. Also shown is the TDEV for that run. After a day if integration, the TDEV is less than 20ps.

As was pointed out, one of the limiting factors for the performance of the locked link is the noise floor of the two color signal. The limiting stability follows the noise floor times the lever arm. Therefore it is important to know how the noise floor scales with link length. Figure 7 show measurements of the 1 second fractional frequency stability as a function of fiber length. As can be seen, the stability degrades with increasing length and shows that the inherent short term stability increases at 3×10^{-16} per kilometer. To ensure that the effect was due to length and not attenuation, the 5km link was remeasured with attenuation equivalent to a 30km link. The results matched the stability of the original 5km link. From this we can infer the performance of longer links. Assuming the same set of transmitting wavelengths, and hence same lever arm, for a 50km link, we should expect the long term stability to behave as 5×10^{-12}. There is evidence that the polarization scramblers used in the link are not properly optimized. It is possible that improvement of their operation may improve the scale of noise with fiber length.

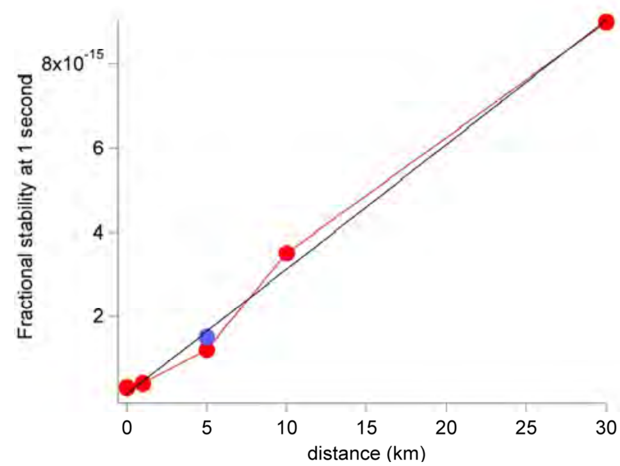

Figure 7. Stability versus length. Plotted is the 1 second stability measurement for the locked link as a function of link length. A fit line corresponding to $1.5\times10^{-16} + 3\times10^{-16}$/km * distance is plotted as well. The blue data point corresponds to a 5km link with attenuation equivalent to a 30km link.

One means of improving the stability of the link is to decrease the lever arm. This can be done by changing the wavelengths used by the transmit laser modules. A larger wavelength separation gives rise to a larger two color signal and smaller lever arm. Figure 8 shows the possible improvement. By using wavelengths at the edge of the C band (shown in green in the figure), there should be an improvement of roughly a factor of two. By extending even further and using a wavelength in the C band and one at

1300nm (shown in grey in the figure), there is almost an order of magnitude improvement in stability at the cost of no longer being able to use erbium doped amplifiers in the link.

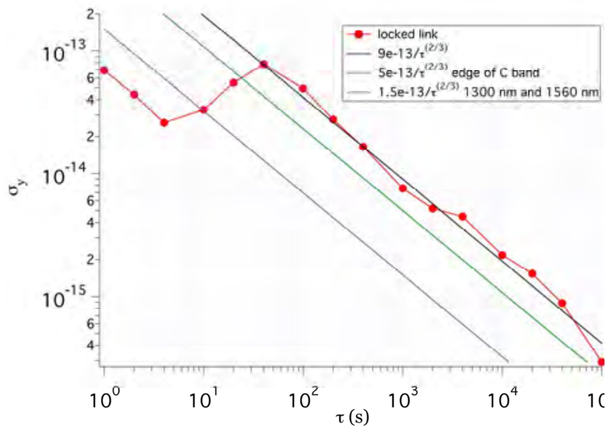

Figure 8. Wavelength improvements. The red curve is the Allan deviation shown in Fig 6. Plotted as well are simulations of changes to the trend line for different wavelength combinations. Black is a fit to the data corresponding to $9x10^{-13}/\tau^{2/3}$. Green is a simulation for a wavelength combination of 1530nm and 1565nm corresponding to a trend line of $5x10^{-13}/\tau^{2/3}$. Grey is a simulation for a wavelength combination of 1560nm and 1300nm corresponding to a trend line of $1.5x10^{-13}/\tau^{2/3}$.

In conclusion, we have demonstrated a one-way temperature compensated fiber optic link. We have shown that by sending two amplitude modulated signals along a fiber optic link, it is possible to recover a record of the thermally induced phase variations and to compensate for them in real time. Some of the length based limitations to performance were discussed as well as possible improvements by appropriate choice of transmit wavelengths. This technology shows promise a viable alternative to two way compensated links when bidirectional access to the fiber is not possible. It also points to easier time transfer through a broadcast protocol as opposed to individual compensated links.

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