

COMPENSATED FIBER-OPTIC FREQUENCY DISTRIBUTION EQUIPMENT

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Abstract

One-way frequency distribution of atomic clock standards has been widely studied, and several architectures have emerged that employ the use of a return path signal to compensate for the effects of temperature and phase noise. These architectures have generally relied upon temperature-controlled delay lines to compensate for fiber thermal effects, and polarization scrambling techniques to minimize the impact of polarization mode dispersion (PMD). These compensation techniques can limit the performance of the system by introducing spurious noise products onto the optical carrier.

Uncompensated one-way fiber optic distribution systems are currently deployed with a demonstrated stability of $2 \cdot 10^{-13}$ (1 sec). Without temperature compensation, this equipment is suitable for intra-facility distribution of hydrogen maser references. However, operation over moderate length inter-facility links (IFL) will degrade the stability significantly, due in large part to the temperature effects of the outdoor or underground fiber cable. The stability can be improved through the use of temperature-compensated fiber cable, but this type of cable is typically an order of magnitude more costly than standard fiber. Furthermore, many locations already have installed dark fiber whose use would be more cost effective.

We are developing a compensated one-way frequency distribution system that is compact, easy to install, and requires neither polarization scramblers nor large, thermally controlled delay lines. The system employs forward and reverse path microwave modulated optical carriers on a single fiber. Electronic compensation is used to correct for path length phase variations, and a novel technique to moderate the PMD without the need for polarization scramblers.

1 INTRODUCTION: PHASE NOISE COMPENSATION PROBLEM

The time and frequency user community, including national laboratories, satellite controllers, and communications centers, have an increasing need for highly stable frequency signal information. Users are developing systems that employ centralized frequency generation standards such as those derived from atomic clocks, and distributing these high-fidelity signals to remote locations. With increasing demand for system diversity and flexibility, remote locations tend to be positioned farther from the central hub. Fiber-optic distribution systems become important for longer distances, due to the lower loss of fiber cable, and have been employed since the 1970s in installations around the world.

Recently, very-high-performance intra-facility fiber optic links have been developed and deployed, providing stability sufficient to transfer hydrogen maser-derived frequency references in intra-facility

applications [1]. Whereas many of the early intra-facility links made use of Fabry-Pérot (FP) laser diodes and multimode fiber cable, these newer links employ single-mode fiber for improved stability and multiple quantum well distributed feedback (DFB) lasers for lower noise. Furthermore, signal conditioning in the links is performed with low phase noise InGaAs PHEMT and HBT amplifiers, and active bias compensation. These links provide better than a -135 dBc phase noise at 1 Hz, and an Allan deviation of better than $2(10)^{-13}$ at 1 sec.

The general characterization of links such as described above is bent-pipe, uncompensated, and point-to-point, as they do not employ frequency translation, the signal propagation is unidirectional, and no environmental information is utilized.

When deployed in long haul, i.e. tens of km, or in inter-facility applications, i.e. from building-to-building, the overall system stability will degrade due to several propagation and environmentally related issues. These factors adversely impact the stability of the recovered frequency signal, limiting the usefulness of the distribution links. However, these limitations are generally environmental, and not a result of the transducers employed in the links; the inherent capability of the optical communications technology, absent the environmental and distortion effects in the propagation medium is in the hundreds of km.

The solution to this problem requires compensation of the added phase noise introduced by the propagation medium.

2 OBJECTIVE

Our objective is to develop a one-way compensated fiber optic frequency distribution system that provides both short- and long-term stability in inter-facility applications, and which is easy to deploy. There is a rich background of work in the time and frequency community from which to draw. A perusal of research results from international laboratory, government, and corporate sources offers a array of material and novel approaches to solving the phase noise compensation problem. A few good references are [2-5]. Making use of this art, and employing novel ideas where applicable, our goal is to develop and manufacture a set of link hardware that is compact, i.e. fits into a standard chassis, and has low installation and operational cost.

Like many of the published compensated link architectures, we employ a return path optical signal that carries information about the environment. The return path signal is used to keep the remote signal phase locked to the primary frequency input. The closed-loop system compensates for thermal variations in the fiber cable, chromatic dispersion (CD) effects, and employs a novel technique for minimizing the detrimental effects of PMD.

3 CAUSES OF INSTABILITY

In order to effectively compensate for the added noise and instability of an inter-facility fiber-optic frequency distribution link, it is important to understand the causes of the instabilities. Here, we identify the key problems, causes, and potential remedies.

There are four primary concerns with regard to fiber-optic stability over IFL distances. These are: thermal instability, CD, PMD, and random environmental effects.

THERMAL INSTABILITY

Thermal instability in fiber-optic cable arises both from the linear expansion of the material and from changes in the refractive index of the fiber core [6]. Furthermore, even though the expansion of silica glass is very low ($\sim 1\text{-}2$ ppm/ $^{\circ}\text{C}$), the expansion of the jacketed cable is usually dominated by the style of jacket, and can range into the tens of ppm/ $^{\circ}\text{C}$ [7]. If we assume a nominal value of 4 ppm/ $^{\circ}\text{C}$, then a 5 km length of fiber will vary by 0.02 m/ $^{\circ}\text{C}$. Propagation of the optical carrier in single-mode fiber is about $2(10)^8$ m/s, leading to a group delay variation of 100 ps/ $^{\circ}\text{C}$, or 20 ps/ $^{\circ}\text{C}/\text{km}$.

In IFL applications, the fiber cable is often buried and, therefore, partially filtered from the rate and extremes of surface temperature variation. Several studies have been performed showing the temperature variations of underground fiber [3,8]. A worst-case is about a 50 $^{\circ}\text{C}$ annual variation with $\sim 10^{\circ}\text{C}$ diurnal cycles. Using our 5 km example, this corresponds to a 1 ns diurnal, and a 5 ns annual instability. This variation is manifested as a significant “aging” degradation in the Allan deviation at a few thousand sec [1]. A good long-term distribution system will need to correct for these thermal instabilities.

CHROMATIC DISPERSION

Chromatic dispersion (the variation in group velocity as a function of optical wavelength) may also affect the performance of the fiber optic link, when link lengths are long. Because different optical wavelengths propagate at different rates, the upper and lower sidebands of an intensity-modulated laser carrier will arrive at the receiver at different times. Nulling will occur when the delay is equal to 180 $^{\circ}$ (see Figures 1 and 2). The first null occurs at a frequency that is dependent on the dispersion characteristics of the fiber and the link length [9]:

$$f_{null} = (4\pi\beta L)^{-1/2}$$

where β is the dispersion parameter and L is the link length. The most common single-mode fiber (Corning SMF-28) has a β of 22 ps²/km at 1550 nm, and ~ 0 at 1310 nm. Using our 5 km example at 1550 nm, the first null will occur at 27 GHz. Provided the length and frequency of operation are low enough that there is little attenuation due to vectored arrival of the sidebands, the overall amplitude effect will not impact the frequency distribution stability. In cases where microwave frequencies are employed at or above the clock resonant frequency, the amplitude effect should be considered for its impact on link noise figure. A very long link (hundreds of km) should include a means of correcting for this dispersion. Generally, for link lengths up to 10 km and frequency bands below 4 GHz, there should be no amplitude nulling dispersion penalty.

A second effect of dispersion is the instability of the group delay of the main envelope due to variation in the laser wavelength. Also, it should be noted that systems employing two optical carriers in forward and reverse (compensating) paths are inherently dependent upon path delay equivalence for accurate compensation. If the laser wavelengths differ, then an uncorrectable variation may result. In an effective distribution link care must be taken to control both the stability of the laser wavelength, and the differential dispersion between multiple wavelengths.

Operation of the link at 1310 nm will virtually eliminate the CD instability, but there are good reasons for choosing 1550 nm nonetheless, including the lower fiber attenuation and the ready availability of long-haul components at 1550 nm. If installing a new system with new fiber, it may also make sense to use dispersion-shifted fiber, which may offer lower-loss *and* lower-dispersion at the desired 1550 nm

wavelength. However, many IFL systems already have fiber installed, and the most common fiber in use is SMF-28, for which we describe the effects here.

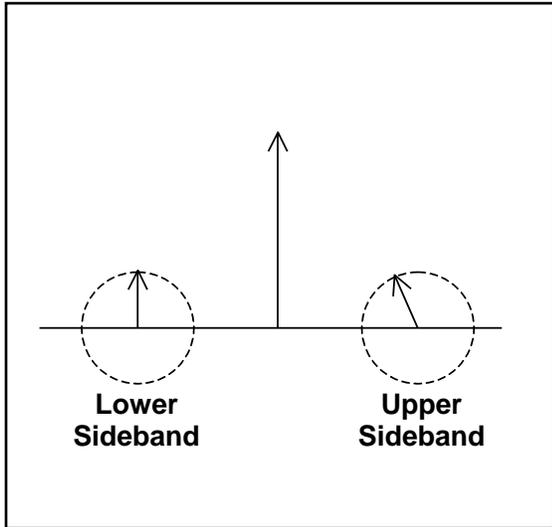


Figure 1. Dispersion causes phase delay between the AM sidebands. The detected signal is attenuated by the cosine of the phase angle. If the phase is 180°, the output is nulled.

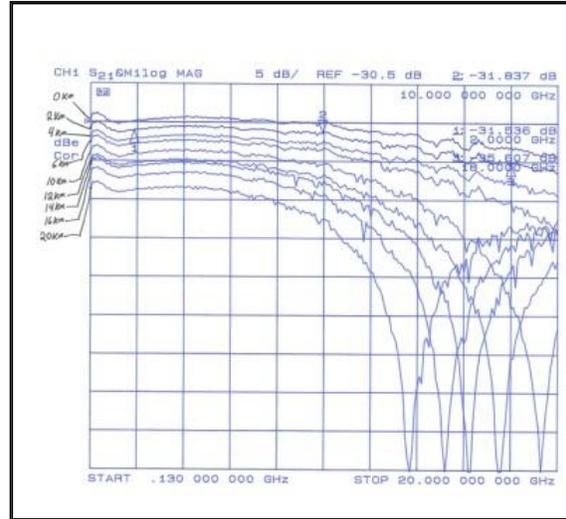


Figure 2. Measured first null frequencies due to chromatic dispersion of a fiber link up to 20 km.

POLARIZATION MODE DISPERSION

A laser signal in single-mode fiber waveguide contains both horizontal and vertical polarizations. Due to microscopic imperfections in the fiber resulting from the manufacturing process, the polarization modes travel at different group velocities in the waveguide. This phenomenon is referred to as PMD. When recombined at the detector, the result is an error phase modulation on the signal (see Figure 3). The polarization states are widely distributed along the length of the fiber, and are unstable; hopping from state to state occurs as a result of temperature, wavelength, and mechanical stress. The resulting group delay has been shown to follow a nondeterministic Maxwellian distribution and can vary significantly [10].

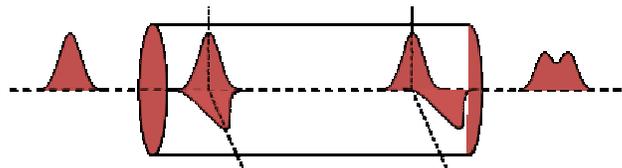


Figure 3. Polarization mode dispersion occurs because constituent polarizations of an optical signal travel at different propagation velocities through the fiber.

A bidirectional compensation network that relies on delay equivalence would compensate for this dispersion, if it were equal in both directions within the time duration of the round-trip path (as would occur with a dominant temperature-dependent variation). However, although the major trend follows the slow-moving temperature variation, the instantaneous PMD will be different along each length because the wavelengths from each laser will be different. Even a small change in wavelength can dramatically affect the PMD [11]. The result is that the compensation network will not correct for the PMD in both directions.

The worst-case maximum PMD of Corning SMF-28e fiber (noncabled) is 0.2 ps/km^{1/2} [12], with a mean value of about 0.06 ps/km^{1/2}. Again using our 5 km example, this amounts to a worst-case of ~ 0.5 ps maximum delay error. When a fiber is cabled, the maximum PMD generally increases, especially if the jacket is tightly bound to the fiber so that mechanical stresses are transferred. Loose-tube jacketing should be considered for long runs, because it minimizes additional stresses.

PMD will be significant for distribution systems that require sub-ns stability. Because it cannot easily be compensated (if at all), PMD may set the stability limit for near-term and present-day systems.

RANDOM ENVIRONMENTAL EFFECTS

This category of instability refers to the “all-other” things that impact the transmission medium, the additive noise, or the nonlinear distortion of the fiber communications link. For example, a truck driving over a buried conduit will impact the PMD and microstresses on the fiber in a nondeterministic manner. Additional examples include local construction activities, maintenance activities in and around fiber junctions, rapid weather-related phenomena, loss of or changes to environmental control facilities, and drifts or instabilities in equipment power and signal sources. These effects share the common trait that they cannot be predicted nor compensated outside the loop bandwidth, and will, therefore, temporarily limit the system stability.

4 COMPENSATED SYSTEM

Figure 4 is a block diagram of a compensating frequency distribution architecture. It has several characteristics that address the instabilities described above, as well as specific user-friendly features. The “local” site is that which contains the reference frequency to be distributed, and the fiber-optic equipment in this location is called the Transmitter. A set of filters and power detectors are used to determine which of three possible inputs (5, 10, or 100 MHz) is present. The detection circuit will switch the input to the appropriate divider network in order to generate a 5 MHz input to the PLL circuit, which is used to phase lock an OCXO reference oscillator. This reference is in turn used to lock a SAW oscillator to 3 GHz. A 100 MHz phase shifter is used to compensate the added fiber noise, and is discussed below. The 3 GHz signal modulates a high-speed, low-noise TEC-cooled DFB laser, which is sent through an optical circulator to the remote site over single-mode fiber.

At the remote site, the equipment is referred to as the Receiver. The incoming laser signal is detected by a high-speed InGaAs P-I-N photoreceiver. This signal is mixed with a 3.1 GHz carrier to regenerate the 100 MHz reference. The 3 GHz signal contains information about the phase deviation in the forward path of the link. This signal is used to lock a PLL circuit to the 3.1 GHz SAW oscillator, which in turn is encoded with the one-way compensation information. This 3.1 GHz signal is transmitted back to the local site over the same fiber. This laser also is dithered with a PMD-spreading bias carrier. The 100 MHz mixer product is buffered and divided to simultaneously provide all three output signals (5, 10, and 100 MHz), regardless of which input signal was used.

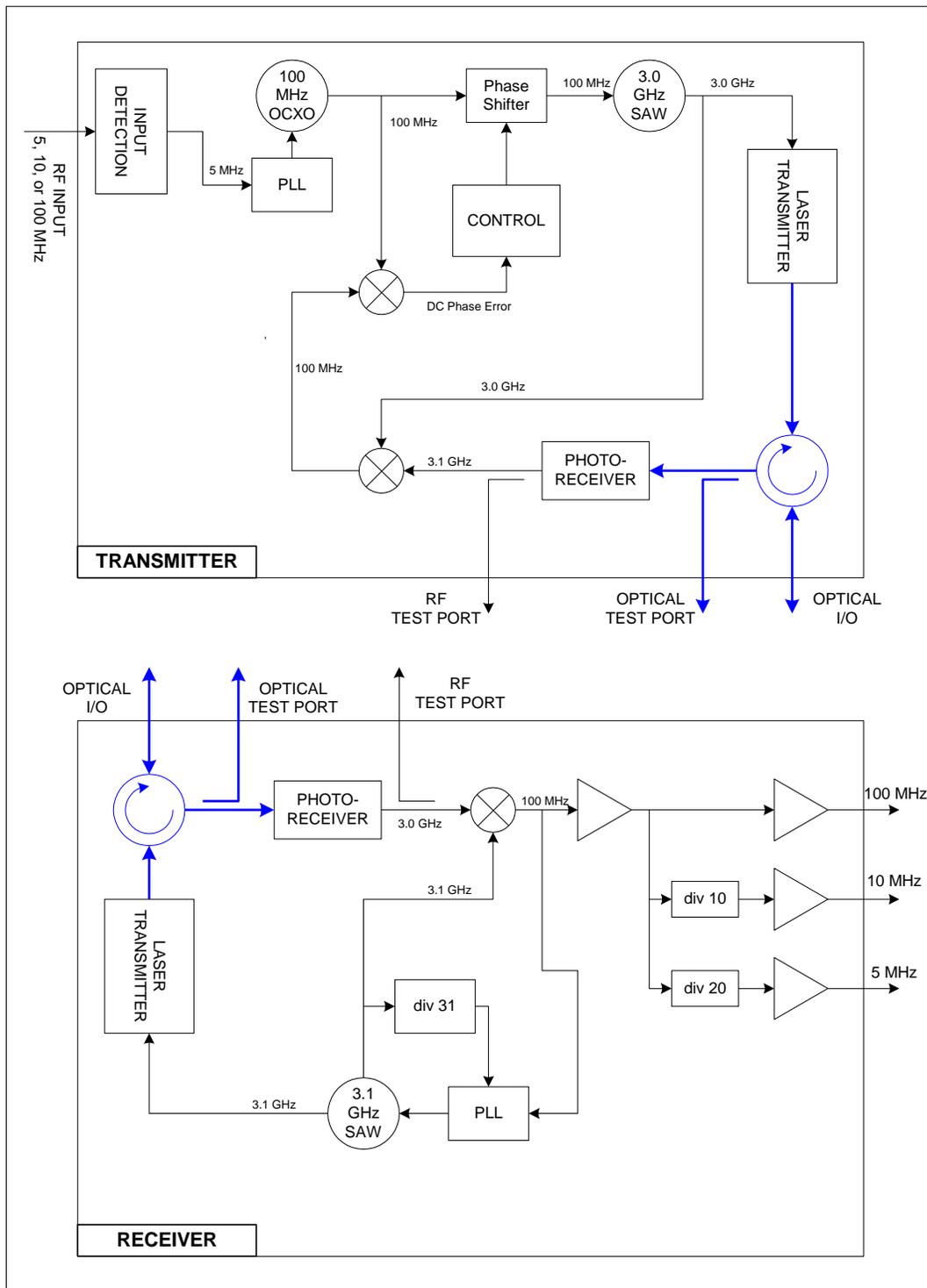


Figure 4. Compensated link block diagram.

Back at the local site, the transmitter detects the 3.1 GHz return signal, downconverts it, and phase-compare it to the 100 MHz reference. The phase difference reflects the two-way phase deviations of the

link. The error signal is used to adjust the phase delay of an electronic phase shifter, with a loop bandwidth within the total two-way delay time (4 km or approximately 20 μ s). In this way, the entire two-way link is phase locked to the incoming reference signal, and the intermediate output at the Receiver is ideally as good as the input reference, in terms of phase noise and Allan deviation.

In practice, this implementation is non-ideal, due to two primary errors: PMD and CD. Even though the link length is relatively short, both PMD and CD worst-case scenarios must be accounted for in the design. Both of these fiber waveguide phenomena have the effect of imparting a different phase deviation in each direction, which can lead to an uncorrectable error.

MODULATION FREQUENCY

We selected nominal modulation frequencies of 3 and 3.1 GHz. In general, a higher modulation frequency is beneficial for two reasons. First, the forward phase deviation experiences a processing gain of 31, as a result of phase locking the 3.1 GHz return signal to the 100 MHz intermediate frequency. This allows for better cancellation in the closed loop. Secondly, the link noise, which ultimately sets the phase noise floor, is roughly the same at the higher frequency as it would be at, say 100 MHz. This makes the error processing gain realizable. The link noise may be limited by laser relative-intensity noise (RIN), and in practice will not be constant at all frequencies; it will peak at around the relaxation oscillation frequency of the laser. A further consideration in the choice of modulation frequency is the maximum modulation frequency of the laser diode and its package. At 10 GHz, for example, the processing gain will be 100 instead of 31, but a more costly externally modulated laser would be required.

WAVELENGTH

We selected the 1550 nm (C-Band) for the optical wavelength. Although this wavelength requires CD correction in long haul systems, it makes good sense for two reasons: First, there are more options for future growth using this wavelength, because external Mach-Zehnder modulators and erbium-doped fiber amplifiers are readily available for this wavelength. Secondly, high-power, low-noise DFB source lasers are readily available on the ITU wavelength grid, which can be directly modulated or used with external modulation devices, further increasing the flexibility of the system design and its future growth potential. The selection of the wavelength will also allow careful control of the effects of dispersion.

PMD SPREADING

For very long links (tens or hundreds of km), many fiber sections of a few km each are typically spliced together. When doing this, the PMD of the entire run tends to regress toward the mean of the Maxwell distribution, which is roughly 0.06 ps/km^{1/2} for Corning SMF-28e fiber. However, we do not want to rely on the statistical approach; we require a method of forcing the regression. Several methods of regressing the PMD compensation have been reported, including the use of polarization scramblers [4]. These devices may consist of piezo-controlled stress mechanisms that impart a mechanical oscillation in different axes of a length of fiber. This, in turn, alters the polarization states of the laser signal, resulting in a root-sum-squared time-averaged value of PMD. These devices, while effective, are large, costly, and difficult to implement. They may require as many as three separate oscillators to drive the piezo circuits. Further, the mechanical stresses may impart additional amplitude-to-phase noise onto the signal, showing up as large spurious outputs in the phase noise.

We have devised an electronic approach that will mitigate the PMD variations, which we refer to as *PMD spreading*. Our approach will exercise all the PMD states in the fiber, thereby averaging out the long-term value to near-equivalence in both directions.

CHROMATIC DISPERSION

To avoid any problem with differential CD, we place both lasers on the same ITU channel, and adjust their center wavelengths to within a few GHz of each other. Ideally, the two signals need not be separated at all, but in order to avoid cross-correlation of the opposite-traveling waves due to optical reflections, we separate them by more than twice the modulation frequency (~ 10 GHz). This small difference in wavelength will result in almost equivalent chirp-related dispersion.

For example, the static differential phase deviation between two wavelengths in the 1550 nm band is related to the differential group delay and modulating frequencies, and the length of the fiber. For two wavelengths near 1550 nm separated by 20 GHz, and with 3.0 and 3.1 GHz modulating frequencies and a length of 5 km, $\Delta\phi$ is ~ 250 μ rad, which corresponds to only about 25 fs.

CD can also lead to uncompensated phase errors due to laser chirp. Laser chirp is caused both by carrier density, due to the modulating field, and thermal effects, due to heat dissipation. Thermal effects have a low-pass effect. This chirp factor, usually expressed in MHz/mA, rolls off rapidly with modulating frequency [14]. Above about 1-2 GHz the chirp effect is minimized. The choice of 3 GHz, therefore, minimizes the residual chirp error; the stability due to modulation chirp should be well below 0.1 ps.

ELECTRONIC COMPENSATION

We compensate the fiber link using an analog (continuous) phase shifter operating the 100 MHz signal. This approach has several significant advantages over fiber-stress and delay-line compensation techniques, which include smaller size, faster response time, and the absence of spurious signals.

An additional benefit of our electronic compensation is the minimization of optical losses associated with delay lines and polarization scrambling. If a link is RIN-noise limited, the noise figure will increase 2 dB for every dB of optical loss. If it is shot-noise limited, it increases one for one [13]. Since the output noise level sets the ultimate phase noise floor, additional optical losses in the system will adversely affect the performance.

ALLAN DEVIATION

Figure 5 shows a series of Allan deviation plots for various systems, including the expected performance for this system. Line 1 on Fig. 5 is measured performance of a Linear Photonics point-to-point (uncompensated) link transferring 5 MHz through 0 km. Line 2 shows the same point-to-point link through 0.5 km of underground temperature-compensated fiber [1]. This test was run for over 8 months to provide long-term data. There is a small degradation between the zero-length and 0.5 km runs.

Lines 3 and 4 are shown on the plot in order to demonstrate the feasibility of obtaining processing gain when using microwave modulation frequencies. Line 3 shows a 1 GHz two-way compensated 43 km link after [4], and line 4 shows a similar 43 km 9 GHz link after [5]. The 1 GHz link shows about 2 orders of magnitude improvement over the LPL 5 MHz link, as would be expected with an error processing gain of 100-200. The 9 GHz link shows further improvement over the 1 GHz link.

Our estimate of performance is based on the expected improvement as a result of the error processing gain when going from 5 MHz to 3 GHz. This is shown in Line 5. We expect to show ~ $2 \cdot 10^{-15}$ at 1 second, and remain below the specification line. Our expected result lies between the 1 GHz and 9 GHz published results. The performance in long-haul systems will be limited by the effectiveness of the CD and PMD correction, and may approach the 9 GHz 43 km link results because it is much shorter.

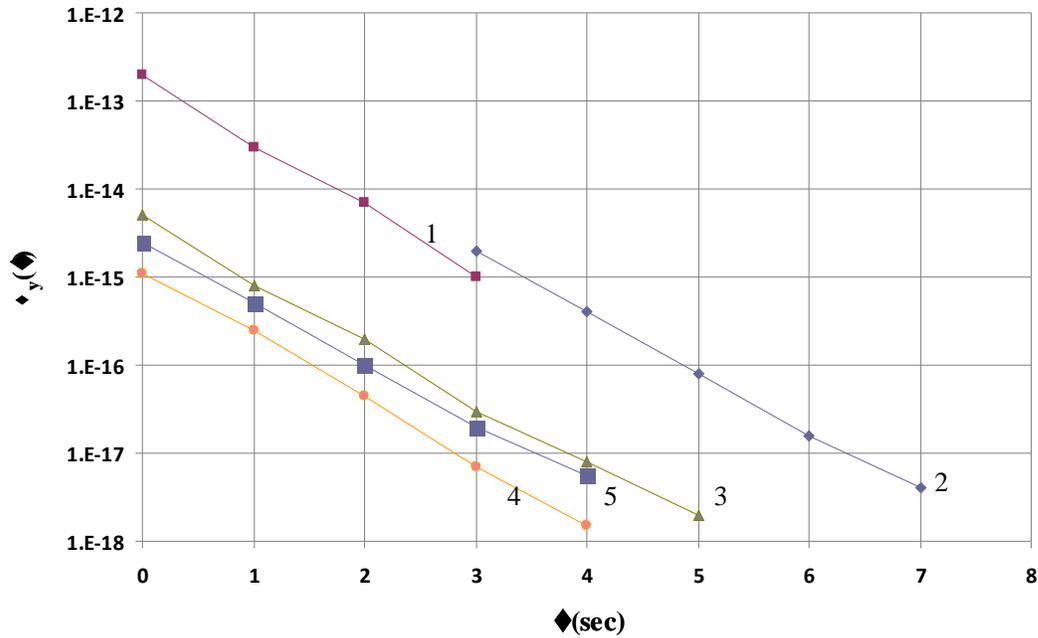


Figure 5. Allan deviation results of similar systems, and expected results of this system.

Line 1: Linear Photonics 5 MHz point-to-point uncompensated link, 0 km [1]

Line 2: Linear Photonics 5 MHz link, temperature-compensated fiber, 0.5 km [1]

Line 3: 1 GHz two-way compensated link, 43 km [4]

Line 4: 9 GHz two-way compensated link, 43 km [5]

Line 5: Linear Photonics model results for system of Figure 4.

5 EXPERIMENTAL RESULTS

We have implemented a portion of this system as of the time of this paper. Because the primary long-term impact on system stability is thermal variation of the fiber medium, we assembled a subsystem that specifically addressed the thermal stability. A block diagram of the experimental subsystem is shown in Figure 6.

In this setup, the 3.0 GHz signal is locked to the 3.1 GHz, within the loop, to generate the 100 MHz local output signal. 3.0 GHz is in turn sent back to the input side to close the lock on the main oscillator. Using the same fiber run will give equivalent path response in both directions, canceling the induced phase noise.

The system was assembled and is shown in the photograph of Figure 7. The fiber spool pictured in the photo was installed in a thermal chamber and the temperature was varied. A phase noise measurement system compared the reference and output 100 MHz signals, from which the phase plots and the Allan deviation response were generated. For comparison purposes, the phase plot was also repeated using a standard uncompensated link such as that described in [1]. The results are shown in Figures 8-10. The same 100 MHz OCXO was used as the input reference for all tests (the OCXO can be seen on the lower right of the Transmitter circuit board in Figure 7).

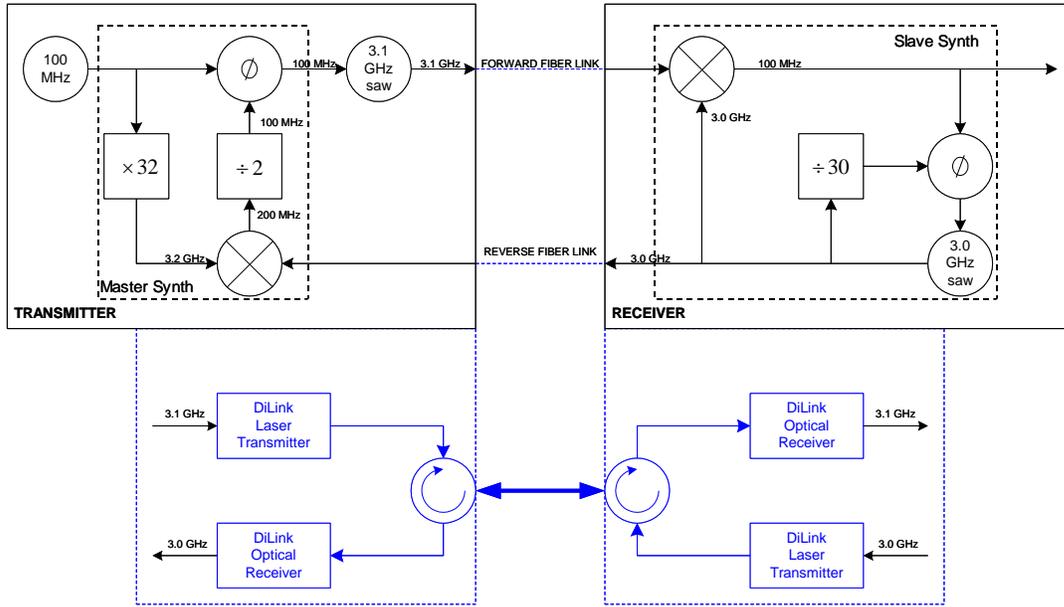


Figure 6. Experimental subsystem assembled and tested at Linear Photonics. This demonstrates the thermal compensation approach through a 5 km link.

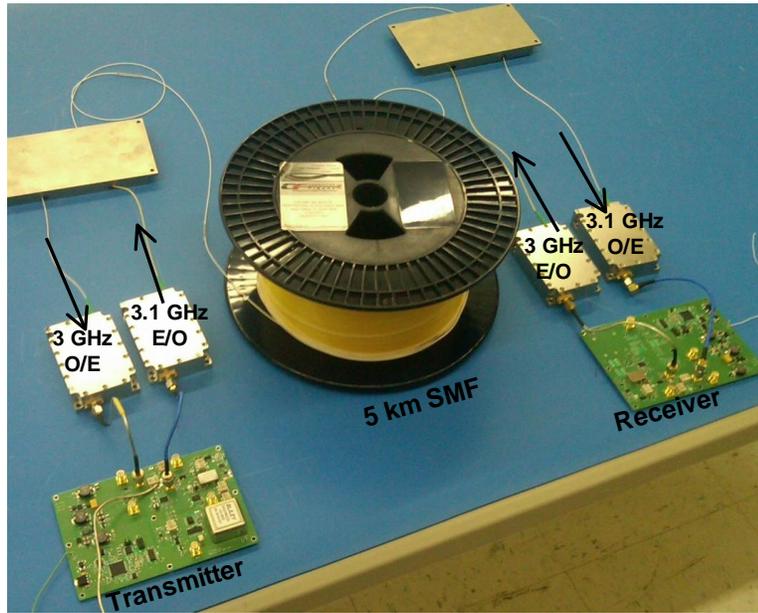


Figure 7. Photograph of the experimental hardware. The 5 km spool of fiber was placed in a thermal chamber, and the output 100 MHz signal was compared to the 100 MHz OCXO input reference.

UNCOMPENSATED RESULTS

The results of the thermal tests are shown in Figures 8 and 9. For the uncompensated link test, we used a standard Linear Photonics TimeLink HF module pair and transferred the 100 MHz input reference directly (bent-pipe, uncompensated, point-to-point). The fiber spool was varied up and down by 10°C, while the phase of the output 100 MHz signal was compared to the 100 MHz input reference. The total variation in phase is approximately 700 ps, or 14 ps/°C/km. This variation, if left uncompensated, would result in unacceptable performance when used in IFLs that rely on long-term stability.

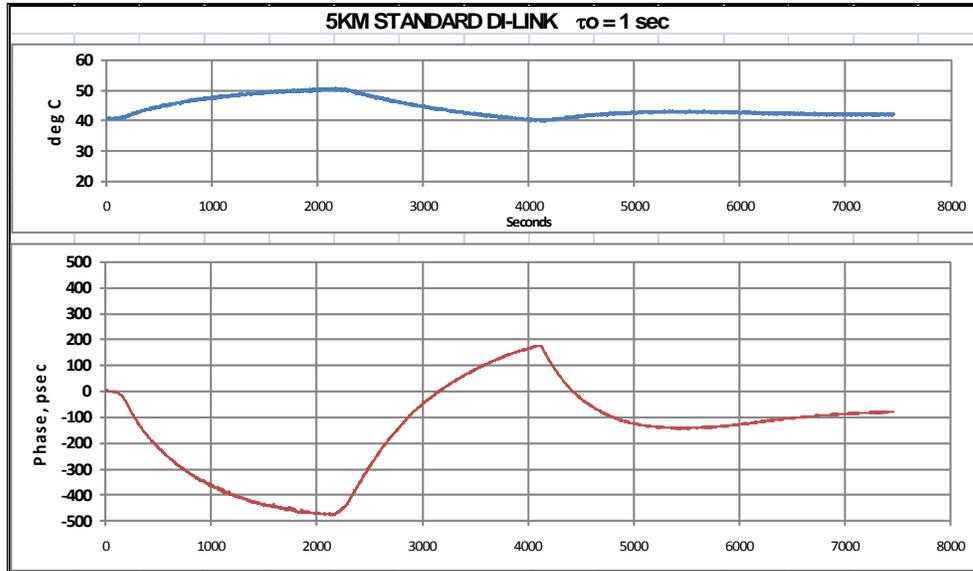


Figure 8. Thermal test results of the uncompensated link. The phase variation with temperature is about 14 ps/°C/km, consistent with expectation.

In Section 1, we estimated a typical value of 20 ps/°C/km. This result was based on phenomenological data obtained in multiple tests at Linear Photonics. The fiber used in this test is better than the estimate primarily because it is not jacketed for underground burial. Depending upon the jacket type, the expansion may be as great as 10-15 ppm/°C.

COMPENSATED RESULTS

The results of the compensated tests are shown in Figure 9. The same style fiber optic link modules were used for this test, only the modulation frequencies were higher (3.0 and 3.1 GHz), and the loop was closed using the circuitry as shown in Figures 6 and 7. The temperature was run up and down by 30°C in this test, in order to effect more variation. The results show virtually all thermal effects have been eliminated; note the smaller 1 ps scale as compared to the uncompensated test. The residual stability is about 2 ps_{pp}.

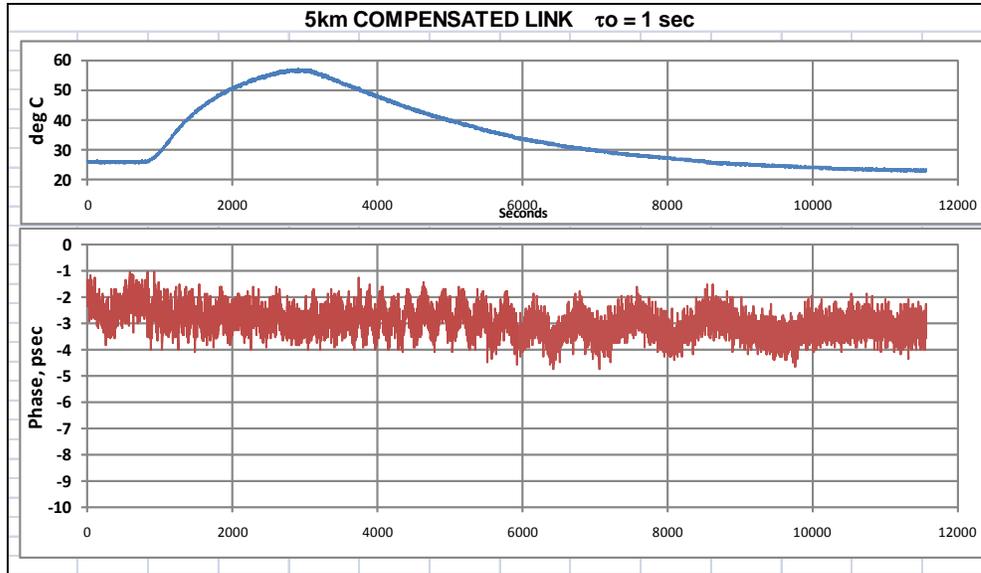


Figure 9. Thermal test results of the compensated link. The phase variation is almost completely eliminated, confirming the thermal compensation technique of the system.

The resulting phase data also reveal a sinusoidal phase variation of about 1 ps_{pp} whose variation rate appears to be related to the rate of change of ambient temperature: when the temperature is stable at the beginning and end of the test, the rate is slow; it increases about an order of magnitude during the most rapid transition of temperature. This result can be attributed to the loop responses of the synthesizers, and is an indication of the overall loop stability. It would be interesting to further investigate loop stability with respect to faster differential rates, but higher rates are unlikely to pose a problem, because the differential rates used in the test were experimentally driven to be several times greater than an expected real-world installation.

SHORT-TERM STABILITY

Shorter time-interval tests were performed on both links at room ambient temperature in order to determine whether the compensated system was adversely affecting the basic fiber optic link performance capability (Figure 10). Both tests were performed through 5 km of fiber. The results indicate that the compensated system is about twice as stable as the uncompensated, although the results are not as good as we project for the final design. At 1 sec, the uncompensated system has an A_{dev} of 10^{-12} , while the compensated is $5(10)^{-13}$. The final architecture, when implemented, should improve the A_{dev} to at least 10^{-14} . One reason for the high A_{dev} is the choice of synthesizer used in the demonstration transmitter board, which will be improved when further tests are conducted.

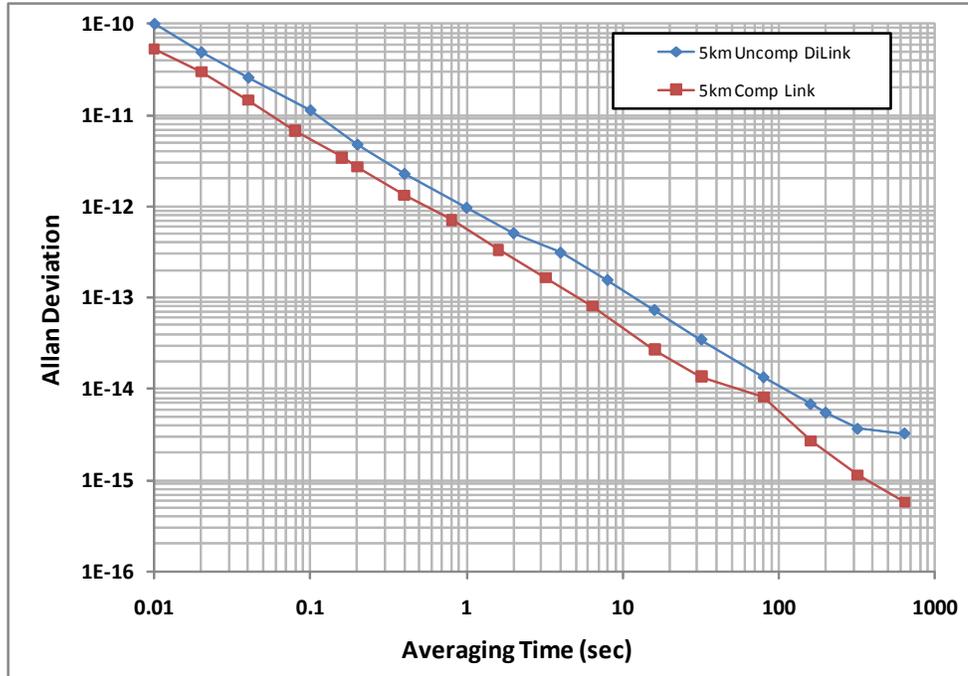


Figure 10. Measured Allan deviation of the uncompensated and compensated links, while held at constant temperature. The short-term stability of the compensated link is about twice that of the uncompensated. Note the start of a thermal-induced plateau in the uncompensated link, which is absent from the compensated link. The goal for the project is $< 10^{-14}$ at 1 sec.

6 CONCLUSION

We have developed a one-way round-trip compensated fiber optic distribution architecture and have assembled a key subsystem that demonstrates several orders of magnitude improvement in phase stability over 30°C and 5 km. The architecture also employs electronic compensation of phase delay and PMD, and will result in a compact final design that will be implemented as plug-in modules to the industry-standard Linear Photonics IFL platform.

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