Active Vibration-induced PM Noise Control in Optical Fibers: Preliminary Studies

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Abstract – **Vibration causes mechanical distortions in fiber-optic transmission lines that induce time (phase) fluctuations. RF systems are increasingly using optical fibers in various ways and must occasionally operate in environments with acoustic and structure-born vibration. A scheme is described which enables electronic suppression and cancellation of vibration-induced spurious phase noise in an optical fiber wound on a spool. The scheme is applied to an opto-electronic oscillator (OEO). Close-to-carrier spectral lines often occur due to mechanical vibration of state-of-the-art oscillators. Passive vibration-suppression schemes (shock mounts, isolation chambers, etc.) do not always adequately reduce discrete line spectra that originate from vibration effects. However, vibration can be readily detected and measured by use of accelerometers. One can correct for these low-frequency vibration artifacts by subtracting a digitally-generated version of the artifacts based on their detection. This approach is generically referred to as "active noise control" and is used for selective noise-cancellation, room acoustic and vibration isolation, vibration suppression in video recording, active magnetic shielding, and other situations that require external noise cancellation or suppression. Active noise control can be applied to virtually all systems and applications that are subject to vibration-induced PM noise. We present simulation results in several cases representing typical vibrating oscillator scenarios. We report progress and experiences with operational hardware.**

I. INTRODUCTION

An optical fiber transmission line provides a low-loss, low-noise delay line for use in delay-line-resonator oscillators and ring-laser gyroscopes, among vast other applications. We investigate the time fluctuations in a spool of fiber that is subjected to acceleration of a few g's by means of a physical actuator. The purpose in this investigation is to assess:

1. vibration sensitivity given in terms of $\phi(t)$ as phase change in the total delay through a length of fiber,
2. the effect of mounting and material properties in which the magnitude of $\phi(t)$ depends on vibration frequency,
3. the degree to which $\phi(t)$ can be correlated with and predicted by an accelerometer so as to electronically cancel or reduce the overall vibration sensitivity of the length of fiber.

Ultimately, we envision a technique which will use a set of sensors, in this case accelerometers, on or near the oscillator's resonator and other vibration-sensitive components that provide vibration characterization as well as compensating signals having a measured correlation with mechanically induced phase fluctuations. Acceleration effects on any system depend on structure-born vibrations and perturbations, and passive dampers act to terminate resonances. In contrast, active systems use sensors which measure system acceleration and compensate for these by means of controlled actuators or other drivers. Generally, active systems allow higher degrees of vibration isolation to be achieved. We propose using a controlled electronic phase correction scheme in a delay-line oscillator, rather than a physical actuator, following the work of Rosati and Filler on quartz oscillators [1]. This paper provides a preliminary study of this proposal. No particular attempt has been made to obtain ultra-low "unvibrated" residual phase noise in any of the setups. The authors are more concerned with testing and improving vibration resistance of low-loss 1550 nm communications-grade optical fiber used as the loop delay in OEO's.

II. MOTIVATION

Oscillators often provide sufficiently low intrinsic phase modulation (PM) noise, but normal mechanical vibrations and accelerations can introduce enough noise to significantly degrade performance of the system. This vibration sensitivity of oscillators is traditionally characterized as a "g" or gravitational sensitivity, and typically produces frequency shifts in oscillators on the order of 1×10^{-9} / g, primarily because of physical deformations in the oscillator. (g, the acceleration of gravity near the earth's surface, is approximately 9.8 m/sec^2.) Other factors include the nonlinear constants and lack of symmetry in the resonator. In the same way, mechanical vibration cause small deformations in electronic components that cause phase fluctuations and thus noise, degrading the performance of electronic systems that depend on high phase stability [2-4].

III. APPLICATION

Low-noise, microwave-frequency oscillators are key components of systems that require high spectral purity (absence of noise). NIST has started a program aimed at actively canceling induced vibration noise in opto-electronic

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oscillators (OEO). The OEO is in the class of delay line oscillators in which the positive feedback mechanism around a gain element (amplifier) is given by odd-integer, pi-radian phase shifts around a fed-back delay transmission line. The OEO implements a low-loss optical fiber as a delay-line resonator as shown in Figure 1[5,6]. The lowest noise at 10 GHz has been achieved by use of a single-loop delay as shown in Figure 1 [7]. A narrow-band RF filter is used to select the oscillating mode. In a delay-line resonator, modes exist at frequencies ~c/nL, where c is the speed of light, and n and L are respectively the index of refraction and length of the transmission line. For the 5 kM length used here, spurious modes appear in the oscillator output signal with a spacing of ~61 kHz. Strategies exist for significantly suppressing them [8-10]. For this discussion, we are interested in the effects of vibration on the phase fluctuations, or time-delay fluctuations, in the optical fiber. Unfortunately, small time-delay fluctuations inside the loop directly map to larger frequency fluctuations at the output of the oscillator [11], which is principly why suppressing fiber vibration sensitivity is so important.

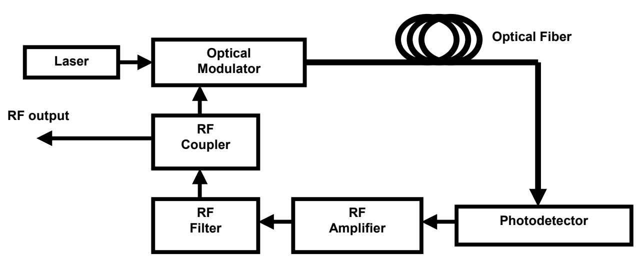

Figure 1. A block diagram of an opto-electronic oscillator (OEO).

IV. EXPERIMENT

Figure 2 shows the setup used for measuring vibration sensitivity on the residual PM noise in a fiber delay line. The setup includes a 10 GHz source whose output signal is split to two channels. The output of a 1550 nm communications-grade laser is sent into an optical modulator which is modulated by one channel of the 10GHz RF signal. This RF-modulated signal is then sent through a 5 km length of fiber that is wound on an aluminum spool. The output light is directed into a photodetector where it is converted back into a 10 GHz RF signal. The second channel of the split 10GHz signal is phase shifted to be in quadrature with the signal through the delay line, and both are then mixed together. The PM noise of the final output signal is then measured.

In the the setup of Figure 2, the mixer is used as a phase detector for two signals in quadrature. Voltage fluctuations correspond linearly to phase fluctuations $\phi(t)$ for $\phi(t)$ << 1 rad. In the case here, such fluctuations are interpreted as the difference of time-delay fluctuations between the optical modulator-fiber-photodetector signal path and the reference-signal path through the phase shifter, adjusted to obtain phase quadrature at the mixer. Time fluctuations have an equivalence to phase fluctuations given by $x(t) = \dfrac{\phi(t)}{2\pi\nu_0}$.

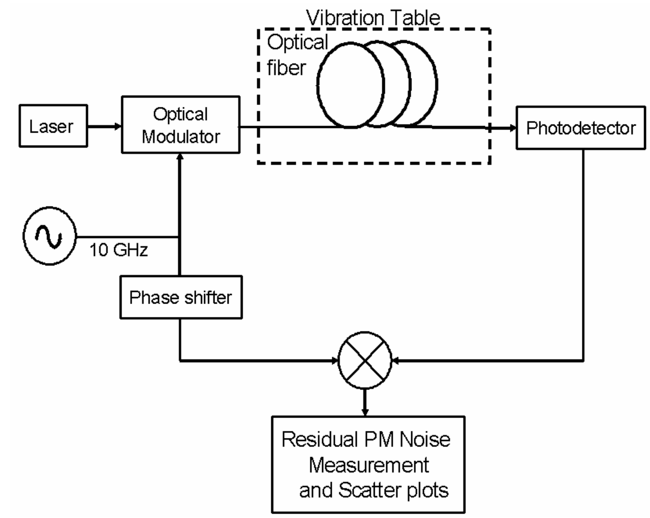

Figure 2. Setup for PM noise measurement of a fiber delay line mounted to a vibration table. We use a phase noise measurement in which a mixer with 10 GHz signals at phase quadrature acts as an analog phase detector.

In order to test the vibration properties of the fiber, the aluminum spool is secured to a vibration table which is driven by a computer-controlled waveform generator and high-power amplifier. An accelerometer mounted to the table provides feedback to the computer, and the output signal driving the table is adjusted for the specified vibration parameters. The spool can be vibrated along any of three axes simply by chaning its orientation on the table. Axis z is normal to the plane of the spool, and axes x and y along the plane are equivalent, since the spool has rotational symmetry (no eccentricity).

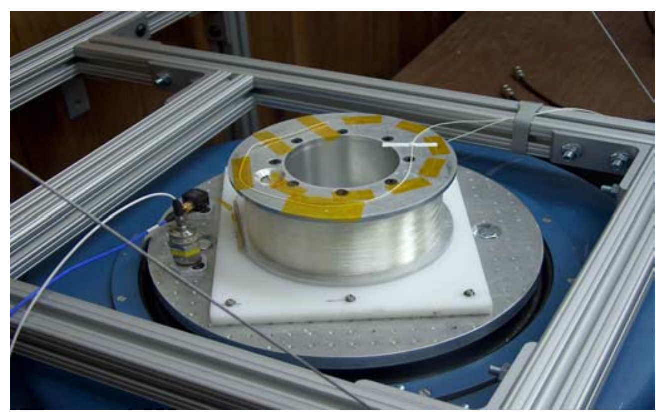

Figure 3. Optical fiber of length 5 km wound on aluminum spool and mounted on vibration table. Orientation as shown presents vibration (acceleration) along z axis of spool.

This setup allows us to measure and analyze residual phase fluctuations due to vibration along the z axis, which represents normal to the spool plane as shown in Figure 3, and the "y" axis, which represents any direction of vibration that is around the edge of the spool. Figure 4 shows the noise levels when the spool is mounted flat on the unvibrated table in preparation for z-axis vibration, or upright in preparation for y-axis vibration. This shows that a change in the orientation of the fiber spool results in essentially no change in the residual phase noise L(f) measured by the setup of Figure 2. The character of L(f) is dominated by the combined noise contributions of the chosen components which make up the optical fiber delay line (RF-to-optical-to-RF). No particular attempt was made to obtain low residual phase noise since it is substantially below the levels when the spool is in a high-vibration environment. Also, this setup with a stationary, unvibrated fiber acts as a frequency discriminator for the 10GHz synthesized source [12]. Consequently, the noise floor is set by the residual noise of components in addition to the noise of the source itself.

V. DATA

To test the effects of vibration, the vibration frequency of the fiber secured to the vibration table was driven at random frequencies between 10 Hz and 2 kHz. The output data from an accelerometer in connection with measured phase fluctuations can be used to produce collrelation, or "scatter," plots. Such a plot is shown in Figure 5 and allows one to view the correlation between phase deviation and acceleration along an axis. This aids in developing strategies for electronically suppressing vibration sensitivity as described next [13].

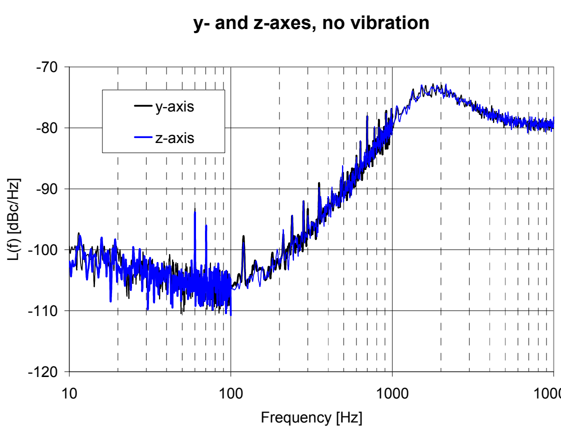

Figure 4. Plot of phase noise for y- and z-axes of fiber spool with no vibration. The function is set by the residual noise of components of Figure 2 in addition to the frequency noise spectrum of the 10 GHz source itself. This checks that a change in the orientation between y and z axes of the fiber spool results in essentially no change in the residual phase noise measured by the setup, as expected.

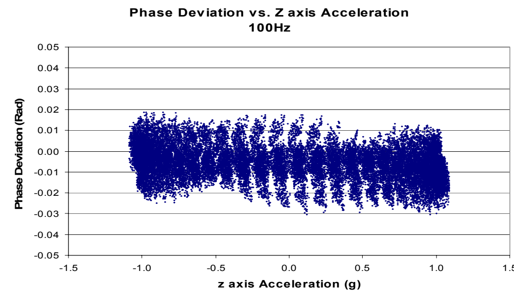

Figure 5. Scatter plot of phase deviation vs. z axis acceleration for random vibration and sine dwell at 100 Hz.

VI. NOISE REDUCTION TECHNIQUE

While the fiber is under vibration, an estimate of the opposite phase of the $\phi(t)$ signal is generated based on vibration sensors, in this case, a z-axis accelerometer. The accelerometer signal is used to modulate the fiber signal's 10 GHz output phase in such a way as to suppress or cancel the induced phase perturbations. This measurement and suppression technique is generically dubbed "active noise control" and is an electronic noise cancellation shown in the block diagram in Figure 6. Figure 7 shows preliminary results and proof-of-concept of active noise control applied to the test spool of optical fiber. The bottom curve is the residual phase noise for 1 Hz < f < 1000 Hz, a portion of which is shown in Figure 4. The topmost curve is the same measurement of phase noise while the spool is vibrated with a constant acceleration of 1 mg^2/Hz, for 1 Hz < f_{vib} < 1000 Hz. The middle curve is the residual phase noise with the noise cancellation turned on. Particularly noteworthy is that the residual phase noise through the spool of fiber is reduced by 15 – 20 dB for 10 Hz < f_{vib} < 100 Hz.

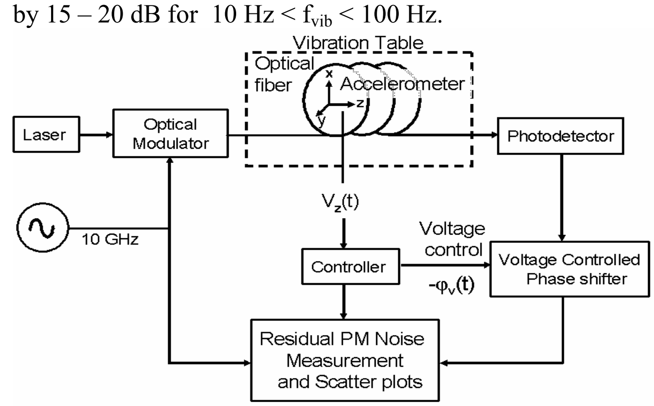

Figure 6. Block diagram of experiment to study vibration-induced PM noise and its suppression in a fiber delay line mounted to a vibration table.

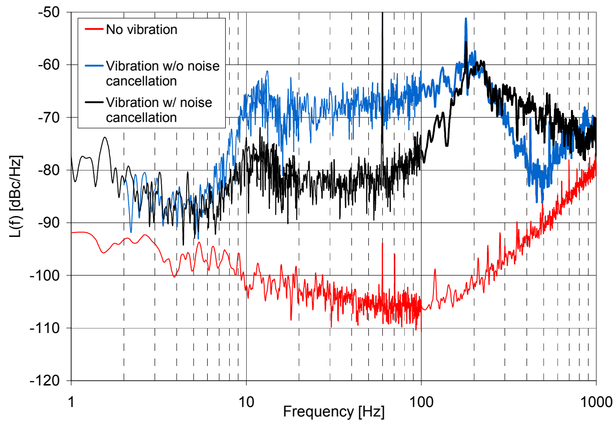

Figure 7. Plot comparing phase noise of fiber with no vibration and under random vibration with and without active vibration cancellation.

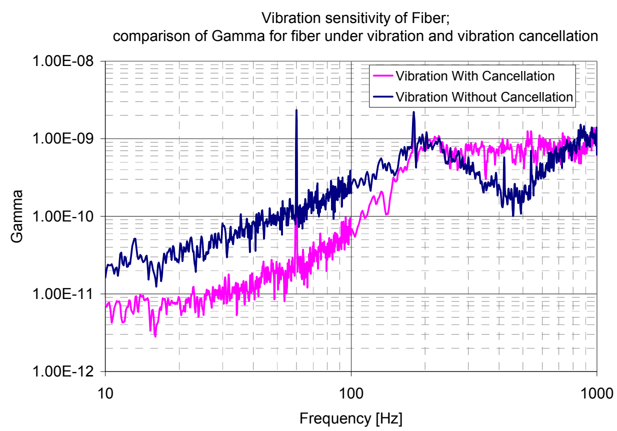

Figure 8. Plot of fiber Gamma $\vec{\Gamma}$ with and without vibration cancellation.

The vibration sensitivity is usually express in terms of Gamma, or $\vec{\Gamma}$, which is the coefficient to normalized fractional frequency fluctuation as:

$$\frac{\Delta \nu}{\nu_0} = \vec{\Gamma} \cdot \vec{a} = y \, ,$$

where, ν_0 is the nominal frequency of an oscillator with no acceleration, $\Delta \nu$ is the frequency change when $\vec{a}$ is the applied acceleration vector. $\vec{\Gamma}$ is the acceleration sensitivity vector. The normalized fractional frequency fluctuation of an oscillator is defined to be y by convention. Since y is proportional to $\dot{\phi}(t)$, the plot of Gamma taken from the power spectra of Figure 7 yields the plot of Figure 8. This is because vibration-induced frequency fluctuations rise as f^2 with respect to vibration-induced phase fluctuations.

It should be noted that such phase perturbations are exacerbated in circuits where phase converts to frequency, such as inside the oscillator loop in the OEO shown in Figure 1. In an OEO under vibration, accelerometer signals can be analyzed as a time series by several possible approaches. The overall goal is to accurately estimate the complex-conjugate of the vibration-induced phase modulation on the otherwise unvibrated optical delay-line in an OEO as depicted in Figure 9. This estimate modulates the oscillator's output frequency by virtue of Leeson's model [11] in such a way as to suppress or cancel the induced in-loop phase perturbations.

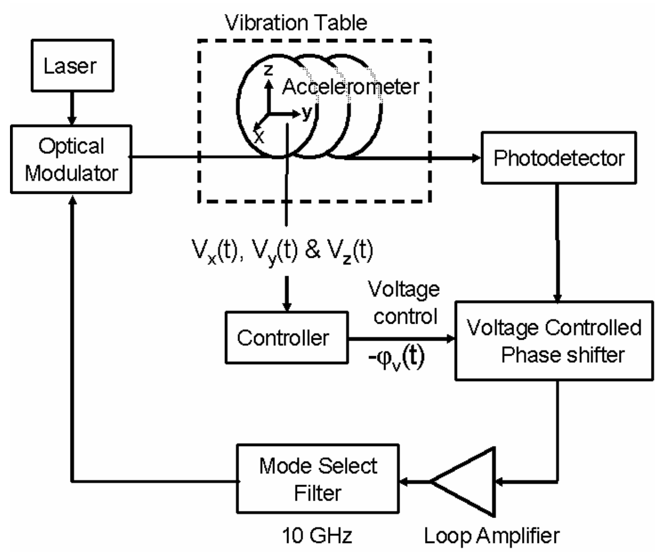

Figure 9. Block diagram of an OEO with the active noise control extended to include all axes as proposed in this paper.

VII. FUTURE PROSPECTS OF ELECTRONIC NOISE REDUCTION

Low acceleration or g-sensitivity does not necessarily mean that phase noise due to acoustic and structure-born vibration is suppressed at all vibration frequencies. While vibration-induced noise-modulation on the spool of optical fiber is generally proportional to g-sensitivity, the proportionality as a function of f_{Vib} can be complicated in the range of audio frequencies of concern here (from a few Hz to 1 kHz) as shown in the preliminary result of Figure 7. Deformations that affect the time-delay fluctuations and, hence, center frequency of an OEO, depend on issues of mounting, elastic properties of the fiber, acoustic resonances, sound and vibration isolation, orientation, and so forth [14]. The results here will be expanded to address the larger problem of reducing vibration sensitivity in any axis of vibration and over a larger range of vibration frequencies.

VIII. SUMMARY

This paper presents data which shows that acceleration-induced phase fluctuations along one axis in a spool of optical fiber can be compensated by a single-axis accelerometer signal. A simple scheme is effective for 10 Hz $< f_{vib} <$ 100 Hz.

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