Cancellation of Vibration-Induced Phase Noise in Optical Fibers

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***Abstract*—Vibration causes mechanical distortions in optical fibers that induce phase fluctuations in the transmitted optical signal. Information encoded on the optical signal by modulation, such as in a radio-frequency (RF)-photonic link also degrades. A feed-forward correction technique is described that enables 20 dB or more cancellation of vibration-induced phase fluctuations in an optical fiber wound on a spool. The scheme is also applied to an optoelectronic oscillator (OEO). The OEO has emerged as an excellent low-noise source that rivals the best electronic RF oscillators over a broad range of offset frequencies. However, close-to-carrier spectral purity of an OEO is degraded mostly by the vibration-induced phase fluctuations in optical fibers when the temperature is held constant. Implementation of feed-forward phase correction in an OEO has shown improvement by almost an order of magnitude in the vibration sensitivity of the oscillator.**

***Index Terms*—Optical fiber, optoelectronic oscillator (OEO), phase noise, vibration sensitivity.**

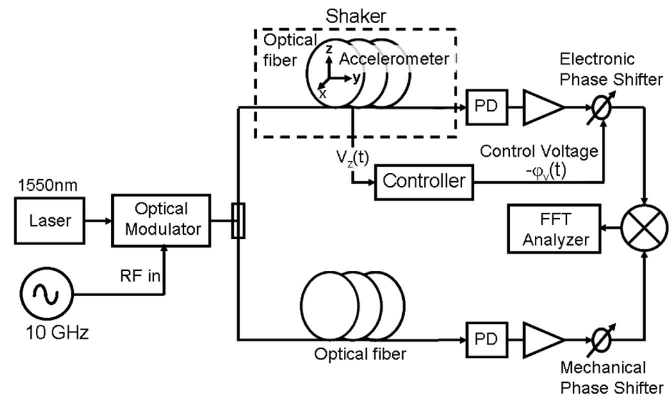

Fig. 1. Experimental setup to study vibration-induced PM noise and its suppression in a fiber delay line mounted on a vibration table.

I. Introduction

Vibration sensitivity establishes an oscillator's phase modulation (PM) noise on many moving platforms such as ground and air vehicles. Oscillators can often provide sufficiently low intrinsic PM noise to satisfy particular system requirements when in a quiet environment. However, mechanical vibration and acceleration in various operating environments can introduce mechanical deformations that deteriorate the oscillator's otherwise low PM noise [1]–[3]. This degrades the performance of an electronic system (e.g., radars or sensors) that depends on this oscillator's low PM noise. Low-frequency vibration noise close-to-carrier can be suppressed either by passive or active vibration-suppression schemes, which has been demonstrated as highly effective in quartz and other oscillators [3]–[5].

Optical fibers are widely used in fiber-optic communication, ring-laser gyroscopes, optoelectronic oscillators (OEOs), and delay line discriminators, among a number of other applications [6]–[8]. In recent years, OEOs have emerged as excellent low-noise sources that rival the best electronic radio-frequency (RF) oscillators. The high spectral purity signal of an OEO is achieved with a long optical fiber that provides very high Q. However, the close-to-carrier spectral purity of this oscillator is degraded mostly by environmental sensitivities, one being the vibration-induced phase fluctuations in its optical fiber [9]. Work on control of environmental noise in optical fiber has previously been implemented in systems where either a portion of the system undergoes vibration or a stable reference is available to measure the induced noise [10]. However, when the entire system is under vibration such as oscillators in moving vehicles and no stable frequency reference is available to measure the induced phase fluctuations, a different approach to vibration mitigation must be taken.

In this letter, we first investigate the phase fluctuations $\phi_v(t)$ of an amplitude modulated light signal in a spool of fiber that is subjected to an acceleration of a few g's by means of a physical actuator. We assess the degree to which $\phi_v(t)$ can be correlated with and predicted by an accelerometer, so it becomes possible to electronically cancel the affect of vibration induced noise in the fiber. Second, we construct an OEO using a 3-km fiber and implement an active noise-cancellation technique inside the oscillator loop. We propose a feed-forward electronic phase correction scheme rather than a physical "anti-actuator," following the early work of Rosati and Filler on quartz oscillators [11].

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II. Vibration-Induced Noise Control in Optical Fiber—Experimental Setup and Results

Fig. 1 shows the setup used to measure the effect of vibration on a fiber delay line using a residual PM noise measurement. It consists of a 1550-nm communications-grade laser whose output is sent into an optical modulator which is amplitude modulated by a 10-GHz RF signal. This RF-modulated optical signal is then split and sent to two channels, each composed of a 3-km length of single-mode fiber (SMF-28) wound on a cylindrical spool, a photodetector (PD), an RF amplifier,

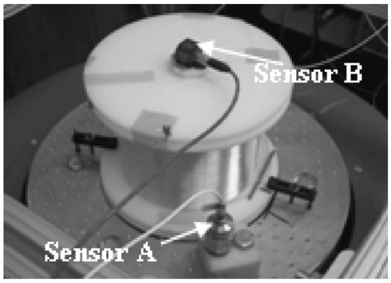

Fig. 2. Optical fiber of length 3 km wound on ceramic spool and mounted on a vibration table. The spool is approximately 11.5 cm in diameter with a length between end caps of 10 cm. Orientation as shown presents vibration (acceleration) along z-axis of spool.

and a phase shifter. The mechanical phase shifter is used to set phase quadrature between the channels, and both are then mixed together. The output voltage noise of the mixer, which is proportional to PM noise, is then measured on a fast Fourier transform (FFT) analyzer.

In order to test the vibration properties of the fiber, one of the 3-km fibers wound on a cylindrical ceramic spool is secured to a vibration table. The cylindrical spool is approximately 11.5 cm in diameter with a length between end caps of 10 cm. The vibration table is driven by a computer-controlled waveform generator and high-power amplifier. An accelerometer mounted to the actuator, as shown in Fig. 2 (sensor A), provides closed-loop feedback to a computer for control of the vibration profile. Sensor B is a tri-axial accelerometer which is used to sense vibrations affecting the fiber spool. Its z-axis is aligned with axis of the spool, and both the x- and y-axes are in the radial directions. For this test, z-axis sensitivity will be the subject of consideration, because the vibration sensitivity of a fiber-on-spool is greatest along this axis [12], [13].

While the fiber is under vibration, an estimate of the opposite phase of the $\phi_v(t)$ signal is generated based on vibration sensors, in this case, a z-axis accelerometer (sensor B) mounted on the top of the spool. An electronic phase shifter, controlled in a feed-forward fashion by the accelerometer, is used to correct the vibration induced phase perturbations of the demodulated 10-GHz signal. Fig. 3 shows preliminary results and proof-of-concept of active noise control applied to the ceramic spool of optical fiber. The bottom curve is the noise floor, and the topmost curve is the same measurement of phase noise while the spool is vibrated with a constant-acceleration white noise of 0.5 $\mathrm{mg}^2_{\mathrm{rms}}/\mathrm{Hz}$, for 10 Hz $< f_{\mathrm{vib}} <$ 2000 Hz, where f_{vib} is the vibration frequency. This frequency range was chosen because this is the full range for our vibration table, adequately covering smaller ranges associated with most applications. The middle curve is the residual phase noise with the noise control on. Particularly noteworthy is that the residual phase noise through the spool of fiber is reduced by 15–25 dB for 10 Hz $< f_{\mathrm{vib}} <$ 2000 Hz. For this experiment a flat frequency response was used for the feed-forward phase correction. A custom-tailored frequency response can be used to achieve better cancellation at different vibration frequencies, depending on the specific vibration properties of the fiber spool.

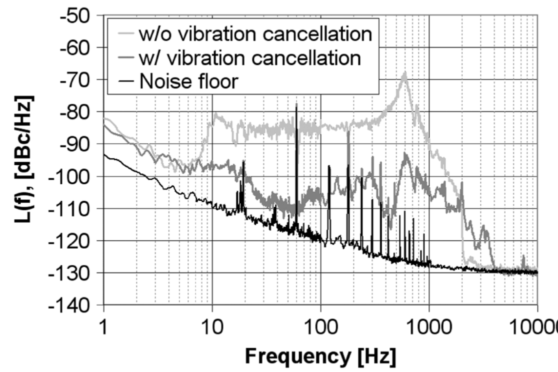

Fig. 3. Plot comparing the residual phase noise of fiber under random vibration with and without feed-forward cancellation. $L(f)$ is the single-sideband phase noise. A constant-acceleration white noise of 0.5 $\mathrm{mg}^2_{\mathrm{rms}}/\mathrm{Hz}$ was used for 10 Hz $< f_{\mathrm{vib}} <$ 2000 Hz; f_{vib} is the vibration frequency. The bottom curve shows the noise floor measured under no vibration. Narrow spurs are EMI pick-up and should be ignored.

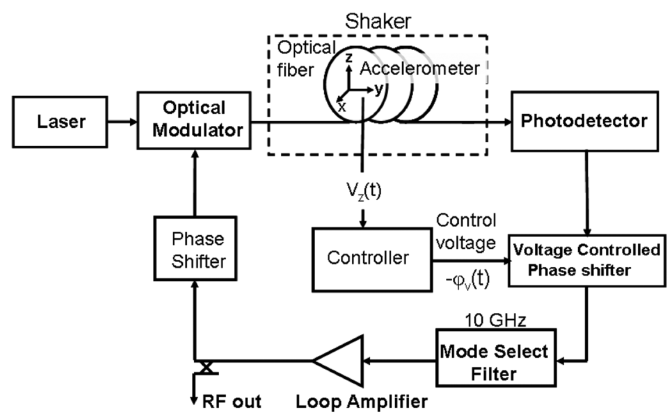

Fig. 4. Block diagram of an OEO with active noise control.

III. Application in OEO

It should be noted that the phase perturbations due to vibration are exacerbated in circuits where phase converts to frequency, such as inside the oscillator loop in the OEO. A typical OEO consists of a length of fiber as a delay-line resonator into which modulated laser light is injected, a detector, an amplifier, and a bandpass filter, with feedback gain and phase arranged so that the device oscillates at different modes with mode spacing inversely proportional to the length of fiber [6]. The first mode for a 3-km fiber used here is approximately 67 kHz from the carrier.

We built an OEO at 10 GHz using a 3-km fiber and implemented the same vibration cancellation technique as described earlier. In an OEO under vibration, an accelerometer signal is used to accurately estimate the complex conjugate of the vibration-induced PM as depicted in Fig. 4. This estimate modulates the oscillator's output frequency by virtue of Leeson's model [14] in such a way as to correct the induced in-loop phase perturbations. PM noise of the 10-GHz OEO with and without vibration, as well as with vibration cancellation, is shown in Fig. 5.

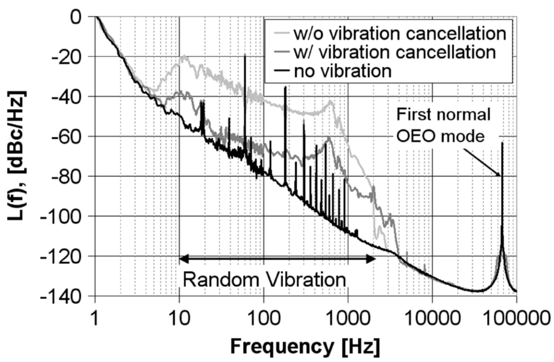

Fig. 5. PM noise of a 10-GHz OEO with and without vibration cancellation. A constant-acceleration white noise of 0.5 $\mathrm{mg}^2_{\mathrm{rms}}/\mathrm{Hz}$ was used for 10 Hz $< f_{\mathrm{vib}} < 2000$ Hz.

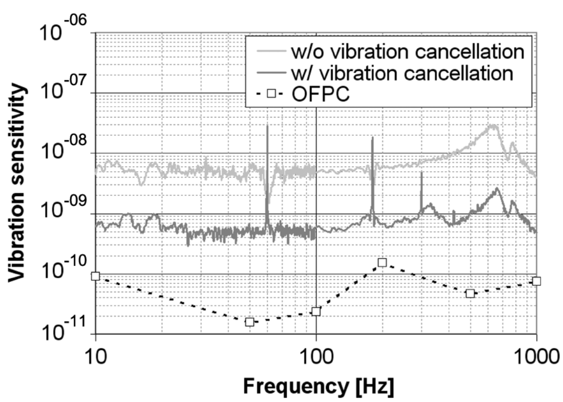

Fig. 6. Plot of z-axis vibration sensitivity of an OEO at 10 GHz with and without vibration cancellation. The top two plots correspond to a constant-acceleration white noise of 0.5 $\mathrm{mg}^2_{\mathrm{rms}}/\mathrm{Hz}$, whereas the bottom curve corresponds to a single-frequency sinusoidal acceleration of 1-g peak. For each sinusoidal frequency, an optimized feed-forward phase correction (OFPC) was used.

The vibration sensitivity of an oscillator is usually expressed in terms of Gamma ($\vec{\Gamma}$), which relates acceleration to normalized fractional frequency fluctuation as [1]

$$\Delta f/f_0 = \vec{\Gamma} \bullet \vec{a} \tag{1}$$

where f_0 is the nominal frequency of an oscillator with no acceleration, Δf is the frequency change when $\vec{a}$ is the applied acceleration vector, also $|\vec{a}|$ is expressed in units of g. For a low modulation index, the single sideband phase noise, $L(f_{\mathrm{vib}})$ and vibration sensitivity in any axis i ($i = x, y,$ or z) are related as

$$\Gamma_i = \frac{2f_{\mathrm{vib}}}{a_i f_0} 10^{[L(f_{\mathrm{vib}})/20]}. \tag{2}$$

Finally, the z-axis vibration sensitivity of the OEO at 10 GHz is calculated by use of (2) and Fig. 5, and is shown in Fig. 6. There is an improvement of almost an order of magnitude in vibration sensitivity over the full range of vibration frequencies tested. A flat frequency response was used for the feed-forward phase correction in this case. However, a custom-tailored frequency response can be used to achieve better cancellation at different vibration frequencies. In order to verify this, the fiber spool was subjected to a sinusoidal acceleration of 1-g peak at 10 Hz, 50 Hz, 100 Hz, 200 Hz, and 1 kHz. The bottom curve of Fig. 6 shows that further improvement in z-axis sensitivity is achieved by optimizing the phase and amplitude of the feed-forward phase correction at these specific sinusoidal frequencies.

IV. Conclusion

We present data that show vibration-induced phase fluctuations along the z-axis of a spool of optical fiber can be compensated by a single-axis accelerometer signal. A simple scheme is described that is effective for 10 Hz $< f_{\mathrm{vib}} < 2000$ Hz. We used this technique in an OEO that improves the vibration sensitivity from 5×10^{-09}/g to 5×10^{-10}/g. Further improvement in the vibration sensitivity of the oscillator can be achieved by means of a custom tailored frequency response. Additional work including corrections for the radial axis is in progress.

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