Vibration-induced PM noise measurements of a rigid optical fiber spool

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Abstract—**The opto-electronic oscillator (OEO) has emerged in recent years as an excellent low-noise source that rivals the best RF oscillators over broad offset frequencies. The main sources of noise in an OEO are the laser and RF modulator, photo detector, loop amplifier, and the long fiber that is needed for high Q. Recent studies have shown that even by using state-of-the-art components and a low-loss long fiber, the phase-modulated (PM) noise of these OEOs fails to meet the theoretical value at offset frequencies close to carrier, from a few hertz to 1 kHz. The main cause for this shortfall is vibration effects on the optical fiber. External, environmental vibration causes mechanical distortions in the fiber that induce time-delay (phase) fluctuations. The spool onto which the fiber is wound is primarily responsible for imparting these vibration-induced delay fluctuations to the fiber and thus diminishing the performance of the OEO. In this paper, we compare the vibration-induced phase fluctuations of a 3 km optical fiber wound on spools made of four materials—metal, ceramic, plastic, and foam-covered plastic. We investigate fiber-on-spool winding and mounting techniques that reduce vibration susceptibility. We present residual PM measurements that compare the vibration sensitivity of an optical fiber wound on these different materials.**

I. INTRODUCTION

Instruments requiring high-performance oscillators are frequently called on to perform reliably in a variety of operating environments. While an oscillator can often provide sufficiently low intrinsic phase-modulated (PM) noise to satisfy particular system requirements when in a quiet environment, mechanical vibration and acceleration in more realistic operating environments can introduce mechanical deformations that deteriorate the oscillator's otherwise low PM noise [1-3]. This degrades the performance of the entire electronic system that depends on the oscillator's low PM noise.

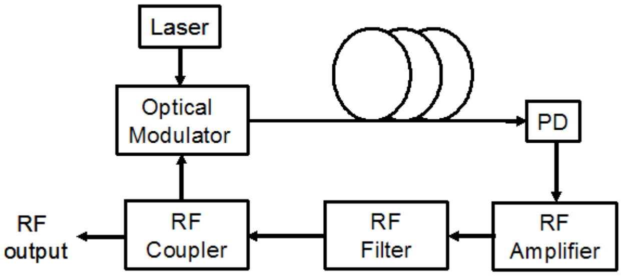

Figure 1. Block diagram of an opto-electronic oscillator (OEO).

Increasingly, optical fibers are being used as the oscillating element in many systems. One notable example is the opto-electronic oscillator, or OEO (Figure 1) [4, 5]. OEOs have emerged in the last few years as an excellent low-noise source that rivals the best electronic radio-frequency (RF) oscillators over broad offset frequencies. The high spectral purity signal of an OEO is achieved with a long optical fiber which provides very high Q. State-of-the-art RF components, such as modulators and amplifiers, are also used to preserve the low noise signal. However, the close-to-carrier (from a few hertz to 1 kHz) spectral purity of this oscillator is mostly degraded by environmental sensitivities, including the vibration-induced phase fluctuations in its optical fiber [6].

The spool onto which the OEO's optical fiber is wound is the primary means of imparting mechanical vibration to the fiber, directly causing delay fluctuations that diminish the performance of the OEO. Plastic and metal are typical materials for fiber spools but can be especially sensitive to environmental effects such as vibration or temperature. Ceramic, a stiff material, is a possible candidate for a spool material that could help the phase noise due to vibration effects in an OEO. In this paper, we will compare spools constructed out of these three materials. Section II describes the specific materials and spool construction, and Section III addresses the fiber and the method of winding onto the spool. The experimental set-up for the PM noise measurements is described in Section IV, and the results are presented in Section V.

II. SPOOL CONSTRUCTION

In order to specifically address the properties of a fiber wound onto metal, plastic, and ceramic spools, our goal was to create spools out of these materials that were as close to the same size and geometry as possible. The basic construction consists of a hollow cylinder fabricated from the test material capped on both ends with POM plastic (Delrin®) end caps specifically machined to fit each material. Each cylindrical piece is approximately 11.5 cm in diameter with a length between end caps of 10 cm. Hollow ceramic cylinders were

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fabricated for us for this application, so we chose plastic and metal materials that were available in these dimensions. Acrylonitrile butadiene styrene, or ABS, is a plastic commonly used in manufacturing; one of its attractive features is its heat resistance. Brass represents metals which are good conductors that transfer heat quickly. Both of these materials are readily available in cylindrical piping with our desired diameter and can be cut to the desired length.

Typically, bare optical fiber purchased from a supplier is supplied on a generic plastic spool. This spool has a layer of thin foam wrapped around it onto which the fiber is directly wound. In addition to our initial three test spools, we created a fourth spool of ABS plastic with a layer of this same foam for a preliminary comparison of the effects of this extra layer on vibration-induced PM noise.

III. OPTICAL FIBER AND WINDING

As well as ensuring that the size and shape of all of our spools were nearly identical, we also wanted the optical fiber to be wound the same on all the spools. Three thousand meters of single-mode optical fiber (Corning's SMF-28) were wound onto each spool using a fiber winder built in our lab for this application.

Precision fiber winding has been studied in great detail [7]. Many methods have been proposed for winding techniques that minimize losses in the fiber due to winding; however, at this initial stage in our investigation, we are concerned only with the relative effects of the spool material. This requires consistency between all our spools, but not that they be meticulously wound in this case. Our main concerns were winding tension and fiber placement.

Figure 2 shows the fiber winder, indicating the mechanisms used to control the tension and the fiber placement. Tension on the fiber is generated by the motor-turned take-up spool pulling the fiber from the factory-wound plastic spool on the other end. A friction brake on the shaft of the factory-wound spool allows free rotation but prevents rocking due to a sudden decrease in tension. Two fixed rollers and one roller on a pivoting arm also adjust to provide a relatively constant tension on the fiber. The computer-controlled lead screw precisely places each consecutive turn of the fiber onto the take-up spool as it rotates. With these tension and placement controls, we can create very similar windings between all of our test spools.

IV. EXPERIMENT

To measure the PM noise of the fiber, we use a residual PM noise measurement system, shown in Figure 3. The output of a 1550 nm communications-grade laser is sent into an optical modulator, then amplitude modulated by a 10 GHz RF synthesizer signal. This modulated optical signal is split between two channels, each consisting of a 3000 m SMF-28 fiber wound on a cylindrical spool, a photodetector (PD), RF amplifier, and a phase shifter. The phase shifter maintains quadrature between the two arms, and a mixer combines the signals, canceling out the laser noise. The output voltage noise of the mixer, which is proportional to PM noise, is then measured on a fast Fourier transform (FFT) analyzer.

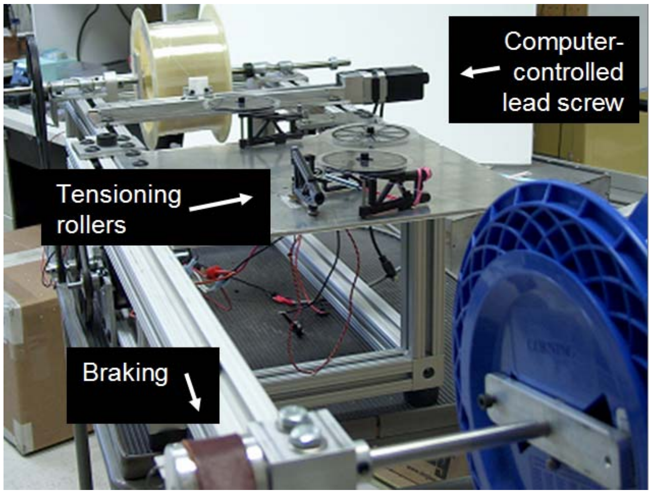

Figure 2. Fiber winder, showing braking mechanism for feeding spool, tensioning rollers, and computer-controlled lead screw.

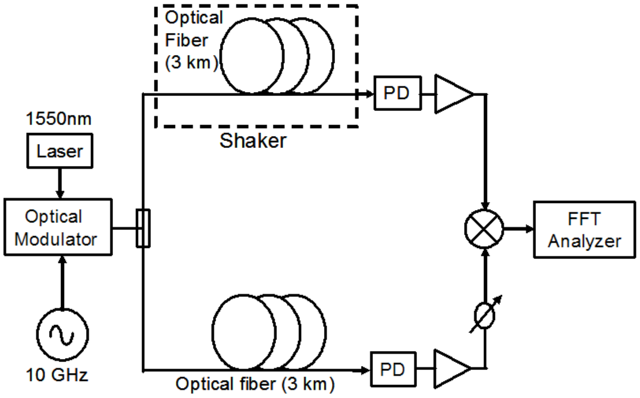

Figure 3. Block diagram of residual PM noise measurement system.

One arm of the measurement system includes one of our test spools. The spool is mounted to a vibration table that is driven by a computer-controlled waveform generator and high-power amplifier. The output signal driving the table is controlled by the feedback of an accelerometer mounted to the table surface next to the fiber spool. The table is driven at specific vibration parameters; in this test, the spool is vibrated with a constant-acceleration white noise of 1 $\mathrm{mg_{rms}}^2/\mathrm{Hz}$ at random frequencies between 10 Hz and 2 KHz. The second arm of the measurement system includes a similarly wound fiber spool of the same length that remains stationary during the test; the same spool is used for all four test spool measurements.

All four test spools are mounted in the same manner for each measurement. Each spool is mounted with the cylinder's axial direction (axis z) normal to the plane of the vibration table (Figure 4). The x and y axes are parallel to the plane of the vibration table; due to the rotational symmetry of the cylinder, these axes are equivalent and may be represented as one single radial axis. However, the scope of this paper will focus only on the z axis since it has been shown that vibration sensitivity is greatest along this axis [8, 9].

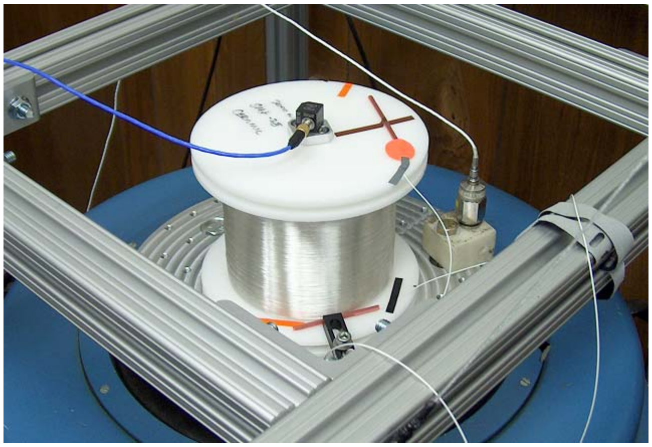

Figure 4. Test spool mounted to the vibration table.

Once the spool is mounted onto the vibration table, a measurement is first taken to observe its noise level while stationary. Then the vibration table is turned on and shaken according to the parameters described above. The PM noise level of the spool is then measured.

As the vibration table is driven during a test, it heats up. This change in temperature is another environmental effect that could also result in higher noise level in the fiber. To observe the effects of the increasing heat, our vibration measurements are done at four different times during shaking: once immediately after the shaker is turned on, and then after 10, 20, and 30 minutes of uninterrupted vibration by the table. A final stationary measurement is taken with all the vibration controls turned off immediately after the fiber has undergone 30 minutes of vibration testing.

V. RESULTS

Figures 5 and 6 show the results of the vibration tests for the four test spools. Figure 5 compares the effect of vibration and heat from the shaker table over time for each test spool. The noise level of the spool under no vibration is shown on each plot as well as the noise immediately after the beginning of the random vibration and after 30 minutes of random vibration. The noise levels of the brass and plastic spools show very little change over the 30 minutes of vibration; however, the noise level is around -60 dBc/Hz. This is compared to the ceramic spool, which has a noise level of near -80 dBc/Hz at the beginning of vibration. However, after 30 minutes, the noise increases to nearly -70 dBc/Hz. Plastic with foam, however, begins at a level just below -80 dBc/Hz, even lower than that of ceramic. After 30 minutes, it does increase slightly, but not as dramatically as that of the ceramic spool.

Figure 6 compares the noise of all spools together at the beginning of vibration and after 30 minutes of vibration. The lower noise of the ceramic and plastic with foam spools is evident for both the beginning of the vibration and after 30 minutes.

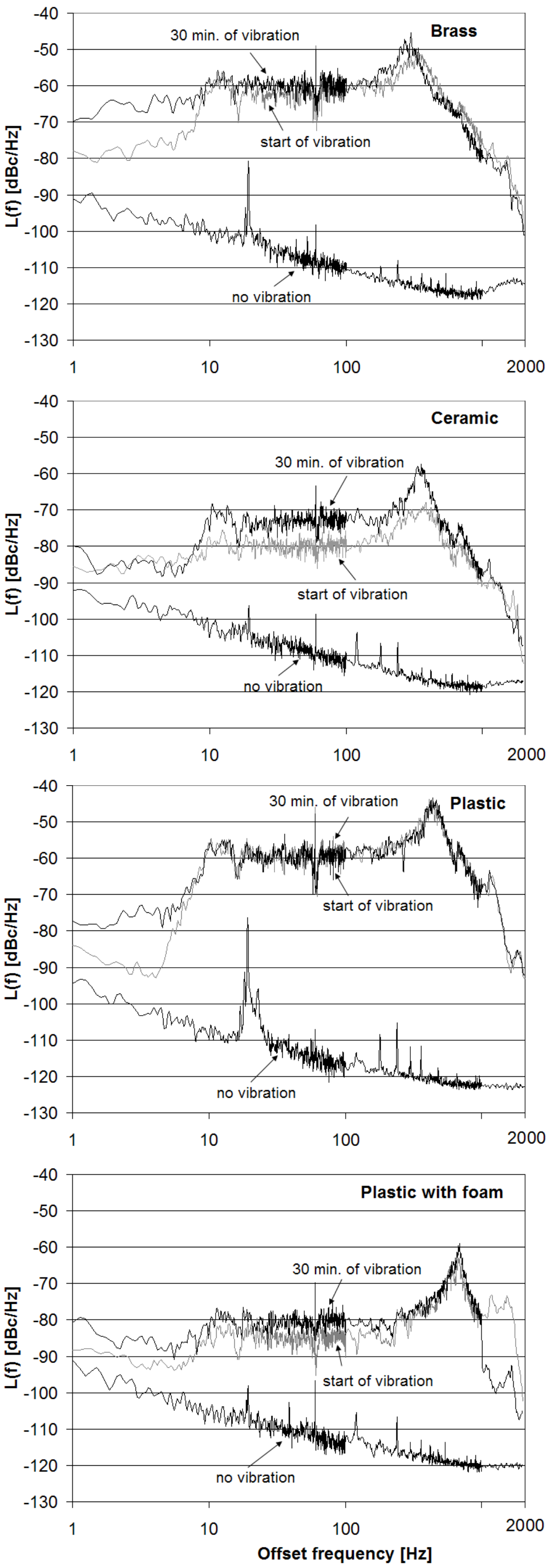

Figure 5. Noise results for four spools, comparing vibration at the beginning of the test to vibration after 30 minutes.

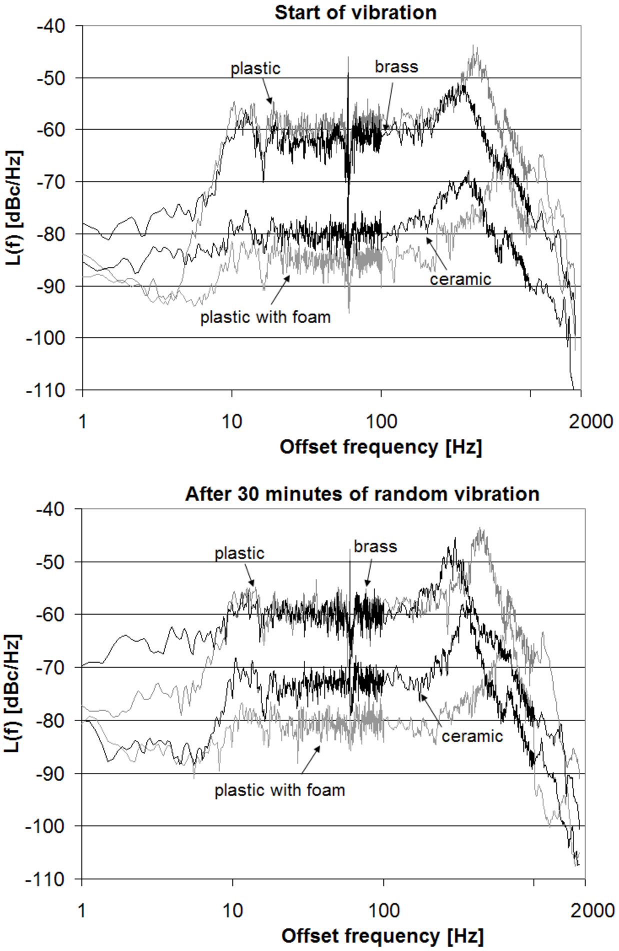

Figure 6. Comparison of all four spools at the beginning of vibration and after 30 minutes of vibration.

VI. RESULTS

These preliminary results are just the beginning of the current study on vibration sensitivity of fibers. Spool material evidently does have a significant effect on the noise performance of a fiber wound upon a spool. The stresses of vibration on the spool material are imparted to the fiber, degrading its noise performance. The ceramic spool seems less affected by the vibration but appears to be sensitive to the change in heat over time. The foam layer over the plastic spool evidently absorbs some of the physical changes of the more sensitive plastic material, causing less stress on the fiber and reducing its noise level under vibration. It does appear to have a slight sensitivity to heating, though not as pronounced as ceramic.

The underlying cause of the change in noise appears to be tension on the fiber from expansion of the spool material due to environmental effects. In the future, we would like to find other materials to test for vibration sensitivity, as well as to explore further how a layer of foam surrounding the material might improve the noise of the fiber under vibration. There may also be methods of using a free-standing fiber coil without a spool. Ultimately, we hope to discover how best to handle the optical fiber in an OEO to fully unlock its potential as a low noise system.

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