Low Vibration Sensitivity Fiber Spools for Laser Stabilization

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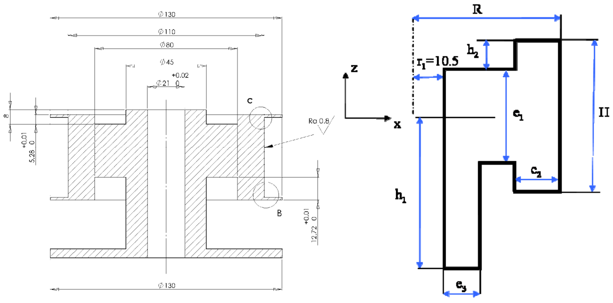
Abstract—**Mechanical vibration induced frequency noise is dominated at low Fourier frequencies in a fiber spool stabilized laser. Environmental vibration causes mechanical deformations in the fiber which induce phase fluctuations and then convert into excess frequency noise to the lasers. Therefore, the spool which supports the fiber plays a critical role in this frequency noise conversion. We have studied several different structures of spool. The preliminary results are about $3x10^{-10}$/m s^{-2} for accelerations along the spool axis. In this paper, we describe the development of a spool design which is optimized for low vibration sensitivity along all spatial directions. Both simulations by Finite Element Modeling (FEM) and vibration sensitivity measurements are presented.**

I. INTRODUCTION

Very low noise lasers is a powerful tool which has a variety of important applications, such as optical frequency standards, gravitational wave detection and generation of low phase noise microwave signals. Currently, the lowest noise lasers are realized by stabilizing laser frequency onto an ultra stable high-finesse Fabry-Perot cavity with PDH method [1-3]. However, this approach requires stable and fine alignment of free space optical elements and high vacuum. A radical alternative is to use an optical fiber delay line as a frequency reference to stabilize laser frequency. Recently we demonstrated that the fiber-stabilized laser showed a comparable frequency noise to the one obtained by PDH locking to a high-finesse cavity for Fourier frequency from 40 Hz to 30 kHz and a level below 1Hz^2/Hz at 1Hz [4, 5].

The fiber stabilized laser is mainly sensitive to mechanic noise, temperature fluctuation, acoustic noise and air-flow. At low Fourier frequencies, the mechanical vibration is critical. First study on low vibration fiber spool was done by Huang et al [6]. They use an anti-symmetric structure to mount two identical fiber spools to obtain very low vibration sensitivity (~10^{-11}/ms^{-2}). We pursuit the effort in this direction and propose to design a spool with similar level of vibration sensitivity or better.



(a) (b)

Fig. 1. (a) Mechanical draw of the spool. (b) Simplified schematic of the spool.

II. DESIGN AND SIMULATION OF LOW VIBRATION SENSITIVITY FIBER SPOOL

Before this design, we studied several configurations, such as simple cylindrical spools and cylindrical spool symmetrically held on a central post, and found that the vibration sensitivity depends strongly on the holding conditions. To overcome this problem, we develop a spool with asymmetric support configuration that would be independent on the holding constraints. The mechanical draw of the spool is shown in Fig. 1 (a). Because the spool has an axial symmetry structure, we restrict our analysis to the half section (Fig. 1 (b)). The spool is made of Titanium because of its stiffness and small mass compared with other metal materials. Some similar works about spool materials have been done and published [7]. The analysis is done by FEM with the hypothesis that fiber delay variation follows the support surface deformation. We test the consistency of the support surface deformation by varying the boundary

978-1-61284-110-6/11/$26.00 ©2011 IEEE

conditions. By optimizing the post length, in such a way, the surface variation under acceleration is independent from the boundary conditions applied on the post base.

This geometry shows another interesting feature. If we plot the FEM calculated vibration sensitivity with different h_2 parameter (see Fig.1 (b)) values as shown in Fig. 2, we can observe that the vertical vibration sensitivity can be zeroed with an optimized value of $h_2 \approx 5.2$mm. Other geometrical parameters (see Fig. 1 (b)) also influence the vibration sensitivity. For example, increasing the central width e_1 moves the null sensitivity point close to $h_2=0$ while increasing the radius R displaces this point towards opposite direction. The increasing of e_1 value reduces the vibration sensitivity coupling to the holding post length and the boundary conditions. The final geometry of the spool is optimized to hold more than 2km of fiber. In addition, a modal analysis is also performed and shows the first resonance of about 1.5 kHz.

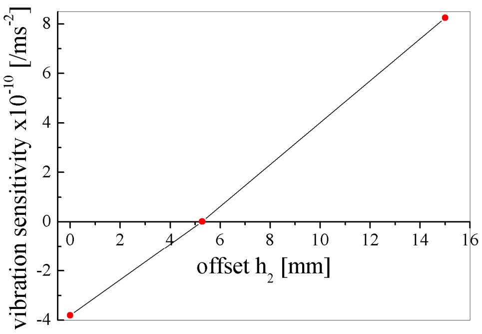


Fig. 2. Plot of FEM calculated vibration sensitivity with different h_2 parameter values

III. VIBRATION SENSITIVITY MEASUREMENT SETUP

The measurement is done in three steps. We first lock the laser source to the fiber interferometer and measure its frequency noise. Then, we shake the fiber spool vertically and measure the transfer function of frequency noise to vertical acceleration. And finally, the vibration sensitivity of the spool is calculated by the transfer function. The schematic of measurement is shown in Fig. 3. The interferometer part is enclosed by dash line.

A fiber laser at 1542.14 nm is used as the laser source, the laser beam goes to the Michelson interferometer passing through an acousto-optical modulator (AOM1). Another acousto-optical modulator (AOM2) is placed into the long arm of interferometer after a 300 m fiber spool and driven by a 70 MHz RF signal. Therefore, the heterodyne detection signal is 140 MHz. We use a home-made low phase noise tunable synthesizer to provide demodulation signal and a low-pass filter converts the demodulation signal into laser frequency correction signal. The correction signal simultaneously acts on a piezo-electric transducer (PZT) stretcher which provides a slow correction on large range and a voltage controlled oscillator (VCO) which drives AOM1 providing fast correction. The fiber spool stabilized laser is combined with a signal from PDH cavity stabilized laser to provide a beat note signal for frequency noise analysis. The fiber spool is housed in an aluminum cylindrical enclosure and placed on an active vibration isolation platform which can be used as a low level shaker by external modulation. In the same time, the other part of interferometer is placed on a passive vibration isolation platform and connected to the fiber spool by two output fibers. The transfer function of frequency noise to vertical acceleration $T_r(f)$ is measured by a vector signal analyzer HP89410. This instrument generates a chirp modulation signal injected in the active vibration isolation platform and then calculates the transfer function between acceleration noise $S_a(f)$ and the measured frequency noise $S_\nu(f)$ as follow:

$$T_r(f) = (S_\nu(f) / S_a(f))^{1/2} \qquad (1)$$

The acceleration is measured by an accelerometer 356B18 (PIEZOTRONICS INC.) placed on the top of the aluminum enclosure. The vibration sensitivity of the spool $\Gamma(f)$ can be presented as:

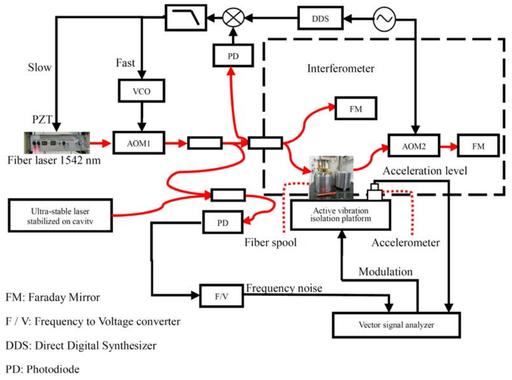


Fig. 3. Schematic of vibration sensitivity measurement, the optical signals are drawn in red while the electronic signals drawn in black

$$\Gamma(f) = \Delta L / (L\Delta V) = \Delta\tau / (\tau\Delta V) = T_r(f) / \nu_0 \qquad (2)$$

Where ΔL, L, Δτ, τ, ΔV, ν_0 represents length variation, total length, delay variation, total delay of the fiber spool and acceleration variation, optical frequency, respectively. Additionally, it should be noticed that the acceleration level is quite low (1mg RMS maximum level). At frequency higher than 60 Hz the acceleration rolls off of about 20 dB up to 110 Hz because of the response of the active vibration isolation platform.

IV. THE RESULTS AND DISCUSSIONS

In our experiment, the reference fiber is standard single mode fiber (SMF-28). Two output fibers of about 0.4 m are used as connections between the fiber spool and other optical components in interferometer. These output fibers are bare fiber (8/125/250µm) and can be looked as "free" fiber because they are only fixed by few points. We notice that the vibration sensitivity of the fiber spool has dependency on the way to fix these fibers. As a consequence, we measure the vibration sensitivity of the fiber spool with different tensions on the “free” fiber. The results are shown in Fig. 4. The vibration sensitivity of new-design spool wound with 300 m fiber is around 5×10^{-11}/ms^{-2}. However, it is strongly influenced by the constraints on the “free” fiber. The Young’s modulus of SMF-28 fiber is about two orders of magnitude lower than that of spool materials. Therefore, the vibration sensitivity of the “free” fiber should be same order higher than that of the fiber wound on the spool. Some studies about fiber vibration sensitivity have been doing in NIST [8]. Moreover, different constraints on the “free” fiber will change its vibration transmission and result in vibration sensitivity variation.

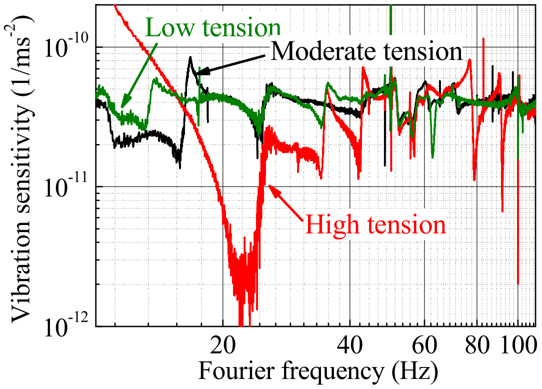


Fig. 4. Vibration sensitivity of fiber spool with different tensions applied on the “free” fiber

The impact of the “free” fiber on the overall vibration sensitivity is still being studied. Nevertheless, several ideas can be carried out to reduce its contribution, such as increasing the fiber length wound on the spool while reducing the “free” fiber length, removing the optical connectors instead of optical splicing. In addition, the studies of vibration sensitivity contributions from other optical components (AOM, FM, etc.) will be performed in the future. In this way, we want to demonstrate a compact ultra-low noise laser without vibration isolation platform that could be used for a variety of precision measurement applications.

REFERENCES

[1] A. D. Ludlow, X. Huang, M. Notcutt, T. Zanon-Willette, S. M. Foreman, M. M. Boyd, S. Blatt, & J. Ye, Compact, thermal-noise-limited optical cavity for diode laser stabilization at 1e-15. Opt. Lett., (2007) 32, 641–643.

[2] J. Millo, D. V. Magalhães, C. Mandache, Y. Le Coq, E. M. L. English, P. G. Westergaard, J. Lodewyck, S. Bize, P. Lemonde, and G. Santarelli. Ultrastable lasers based on vibration insensitive cavities. Phys. Rev. A (Atomic, Molecular, and Optical Physics), (2009) 79, 053829.

[3] S. A. Webster, M. Oxborrow, S. Pugla, J. Millo, and P. Gill, Thermal-noise-limited optical cavity. Phys. Rev. A (Atomic, Molecular, and Optical Physics), (2008) 77, 033847.

[4] F. Kefelian, H. Jiang, P. Lemonde & G. Santarelli, Ultralow-frequencynoise stabilization of a laser by locking to an optical fiber-delay line. Opt. Lett., (2009a). 34, 914–916.

[5] H. Jiang, F. Kefelian, P. Lemonde, A. Clairon & G. Santarelli, An agile laser with ultra-low frequency noise and high sweep linearity. Opt. Express, (2010)18, 3284–3297.

[6] S. Huang, M. Tu, S. Yao & L. Maleki, A ’turn-key’ optoelectronic oscillator with low acceleration sensitivity. FCS’2000 , CL00–0626.

[7] J. Taylor, C. Nelson, A. Hati, N. Ashby & D. Howe. Vibration-induced pm noise measurements of a rigid optical fiber spool. Frequency Control Symposium, 2008 IEEE International , 807–810.

[8] A. Hati, C. Nelson & D. Howe, Vibration sensitivity of optical components: a survey. Joint Conference of the IEEE International Frequency Control Symposium and European Frequency and Time Forum, 2011.