Ultra Low Frequency Noise Laser Stabilized On Optical Fiber Spool

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***Abstract*—In this paper, the development of an ultra low frequency noise laser has been presented. This laser is obtained by frequency stabilizing a fiber laser to a 1-km fiber length-unbalanced Michelson interferometer with heterodyne detection configuration. The laser frequency noise power spectral density is reduced by more than 40 dB for Fourier frequencies ranging from 1 Hz to 10 kHz, corresponding to a level well below 1 Hz^2/Hz over the whole range. Between 30 Hz and 10 kHz, the frequency noise of the laser is shown to be comparable to that obtained by Pound-Drever-Hall locking of the laser to an ultra-stable cavity. Moreover this laser has the great advantage of no optical alignment and no polarization adjustment due to the utilization of an all-fiber system. It is therefore intrinsically more compact, light, robust and flexible than cavity-based systems. This stabilization technique allows the frequency tunability of the low noise laser.**

INTRODUCTION

Very low frequency noise lasers are important tools for many applications such as high resolution spectroscopy, optical atomic clock local oscillators, interferometric sensors (including gravitational wave detection), and coherent optical communications systems. Laser frequency noise is usually reduced by locking to an ultra-stable optical cavity using the Pound-Drever-Hall method [1]. It leads to fractional frequency instability lower than 10^{-15} for 1 s averaging times and subhertz linewidth [2]. However this method requires fine alignment of free space optical components, tight polarization adjustment and spatial mode matching. Moreover, ultra-stable cavities are relatively expensive, bulky and fragile. A fiber delay line is widely used for laser frequency noise and linewidth measurement, and consequently it can be used as an extra reference for laser noise rejection. This noise rejection approach has been implemented by several groups in the last two decades [3] [4] [5] [6]. The results show that the fiber stabilized laser is still more than 20 dB noisier than an ultra-stable cavity stabilized laser. Here, we present an improved fiber stabilized laser, which is less noisy than previous system and include new features such as the frequency tunability. This opens the way to new applications.

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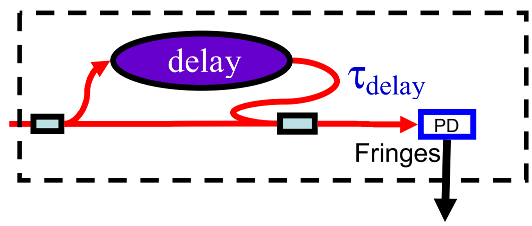
PRINCIPLE OF OPERATION

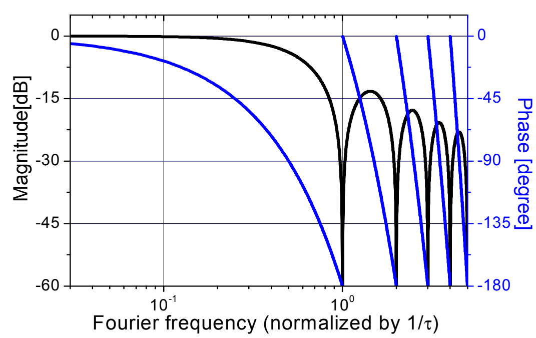
The length unbalanced delay line interferometer is shown in Fig. 1a. It converts the laser frequency noise into the phase noise with transfer function:

$$Tf(f)=(1-e^{-i2\pi\tau})/if \text{ [rad/Hz]} \qquad (1)$$

where τ is the unbalance time delay of the interferometer. Through negative feedback of the output of the interferometer to the laser control port we can frequency-lock the stabilized laser frequency to the fiber delay. According to the transfer function, we can calculate the frequency response of the



(a)



(b)

Fig. 1. (a) Length unbalanced interferometer scheme, (b) Frequency response of the interferometer magnitude and phase.

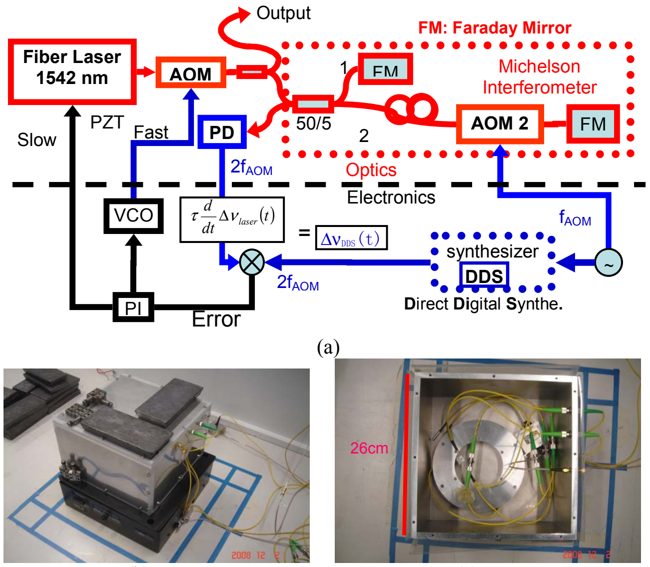


Fig. 2. Experimental setup: (a) Frame scheme: DDS (Direct Digital Synthesizer), VCO (Voltage Controlled Oscillator), AOM (Acousto Optical Modulator), FM (Faraday Mirror), PD (Photo Diode), (b) Picture1 of the Michelson interferometer part, (c) Picture 2 of the Michelson interferometer

interferometer. The magnitude (black line) and phase (blue line) of the frequency response are shown in Fig. 1b. For low frequencies, the magnitude is approximately equal to $2\pi\tau$. This means the sensitivity increases with the unbalance length. At integer times of $1/\tau$ frequencies, the interferometer has a null response. The unbalance length of the interferometer has to be chosen according to a trade-off between the sensitivity and the control bandwidth.

EXPERIMENT SETUP

Fig. 2 shows the experimental setup, where the optical signal, RF signal and low frequency signal are drawn in red, blue and black respectively. The main difference from our previous setting [7] is the use of a tunable synthesizer instead of the RF frequency doubler. As a Michelson interferometer is used, with two Faraday mirrors at the ends of the arms at the output of the interferometer, no polarization controller is required to optimize the beat-note signal. The new feature introduced with respect to previous delay-line stabilization techniques is the use of a heterodyne detection configuration [8]. An AOM is inserted into one arm of the interferometer giving a frequency shift to twice the AOM modulation frequency (f_{AOM}). The output is a heterodyne beat-note signal around this frequency at the photodiode output. This is demodulated using a $2xf_{AOM}$ frequency signal provided by a tunable synthesizer synchronized with the AOM modulation signal. The heterodyne detection is less noisy than the conventional homodyne detection and allows for tuning of the laser frequency. Indeed, a tunable frequency offset ($\Delta\nu_{DDS}$) can be added to the $2xf_{AOM}$ frequency demodulation signal by the synthesizer. When the control loop is closed, the laser frequency will follow the function:

$$\Delta\nu_{laser}(t)=\int_0^t \Delta\nu_{DDS}(t)\, dt/\tau \qquad (2).$$

The laser frequency can be tuned by adjusting the frequency offset of the DDS. In addition to the PZT control, we have a fast laser frequency control by using an AOM. This is good for high frequency noise rejection. The length of fiber delay line we use is 1 km and the frequency noise of the fiber stabilized laser is measured by analyzing the beat-note signal with an ultra-stable cavity stabilized laser [9]. In this set-up, all interferometer components are pigtailed off-the-shelf elements. Therefore we do not need to do any optical alignment and it is simple and robust. All of the optical interferometer parts shown in Fig. 2b, 2c are housed in an aluminum box with thermal isolation (Mylar), whose size is 26 cm x 26 cm x 16.5 cm, sitting on a commercial compact vibration isolation platform. Inside the box, the fiber spool is laid in another a small toroidal aluminum case. Note that the temperature fluctuation in the laboratory is about 1 degree peak-to-peak and the interferometer is not under vacuum like an ultra-stable cavity.

MEASUREMENT AND DISCUSSION

Fig 3 shows the experimental results. Compared with the frequency noise of two reference lasers (black trace), the frequency noise of the beat note between the fiber stabilized laser and the reference laser (red trace) is no more noisy. this means that the frequency noise of the 1 km fiber stabilized Laser is at least as low as one of the ultra-stable cavity stabilized lasers. At low frequencies the frequency noise is about 10 dB higher than the reference laser. This is caused by several sources: power fluctuations of RF and optical signals, mechanical noise or temperature fluctuation of the laboratory. However, in the frequency range from 1 Hz to 10 kHz, the frequency noise is well below 1 Hz^2/Hz. Based on Wanser`s thermal noise analysis [10], the thermal noise floor can be calculated by using the following equation:

$$S_{\nu-thermal}(f)=\frac{k_B T^2}{\lambda^2 L}F\left(f, D_{th}, \frac{dn}{dT}, n, \kappa\right) \ [\mathrm{Hz^2/Hz}] \qquad (3)$$

where k_B is Boltzmann constant, T is temperature, λ is laser wavelength, L is the fiber length, F is a function of fiber parameters, f is the Fourier frequency, D_{th} is the thermal diffusivity, n is refraction index , κ is the thermal

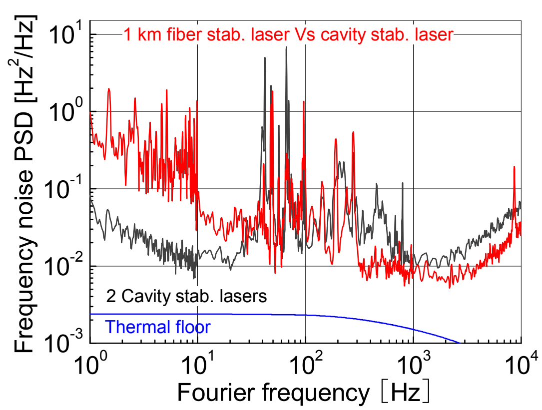


Fig. 3. Frequency noise of fiber stabilized laser and a reference laser (red trace), frequency noise of two reference lasers (black trace), thermal noise floor (blues trace)

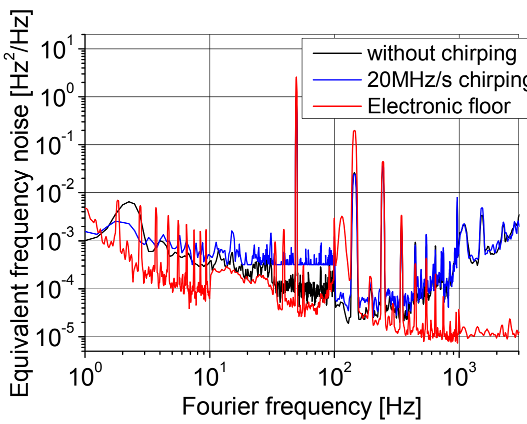


Fig. 4 Error signal equivalent frequency noise of no-chirped laser (black trace), error signal equivalent frequency noise of 20 MHz/s tuned laser (blue trace) and electronic induced frequency noise (red trace)

conductivity. For a 1 km SMF-28 fiber stabilized laser, the thermal floor is represented by the blue trace shown in Fig. 3. The frequency noise of the fiber stabilized laser is not limited by the intrinsic thermal noise of the fiber. The thermal noise floor is already very low and it can be further reduced by using a longer fiber or a low temperature sensitivity fiber.

When the laser is locked to the fiber interferometer, the laser frequency noise comes entirely from three parts: fiber induced frequency noise, electronics induced frequency noise and error signal equivalent frequency noise, which is the uncontrolled laser noise. The laser frequency noise can be described by the following equation:

$$S_{\nu\,\text{laser}}(f) = S_{\nu}(f)_{\text{error}}/(2\pi\tau V_{\text{peak}})^2 + S_{\varphi}(f)_{\text{elec}}/(2\pi\tau)^2 + S_{\varphi}(f)_{\text{fiber}}/(2\pi\tau)^2 \quad (4)$$

where $S_{\nu}(f)_{\text{error}}$ is noise of error signal, V_{peak} is the maxim value of error port output, $S_{\varphi}(f)_{\text{elec}}$ is phase noise of electronics, $S_{\varphi}(f)_{\text{fiber}}$ is phase noise of fiber. The first term is the contribution of uncontrolled laser noise, which is shown in Fig. 4 in black (blue) without chirping (with chirping 20MHz/s rate). The error signal equivalent noise is far below the laser frequency noise during tuning. The second term is the contribution of electronic noise, which is the red trace shown in Fig 4 and is well below the laser frequency noise also. If the third item does not induce too much additional noise, the tuned laser is low frequency noise. As the interferometer part is not changed during frequency chirping, the additional noise of the interferometer induced by the frequency chirping should be mainly due to the chromatic dispersion fluctuation. According to a measurement report of Luna Innovations Incorporation [11], the chromatic dispersion coefficient variation with respect to wavelength is less than 4 ps/(km.nm^2) over the range 1540nm-1552nm for a SMF-28 fiber. The calculated frequency fluctuations due to the chromatic dispersion fluctuation are less than 10^{-14} Hz^{-2}, which give less than 4 Hz/s for a 20MHs/s chirped laser. It is reasonable to suppose that the laser has low frequency noise when it is tuned at such a speed. The tuning span is the mode hop free range of the laser (a few tens of GHz). A digital lock is also implemented by using a dead-time free frequency counter as a phase detector and controlling the DDS frequency. The laser can be used as a low noise optical tracking oscillator. For example for the Doppler tracking of an optical signal from a low orbit satellite (~1000-km), which shows a maxim tuning rate of about 60MHz/s.

CONCLUSION AND PERSPECTIVE

A fiber stabilized laser with frequency noise at least 20 dB less than the previous results of laser stabilization using fiber-delay lines in the range from 1 Hz to 100 kHz has been developed. This is due to a longer delay fiber and heterodyne detection configuration. The fact that the laser keeps its low noise feature at tuning rates up to 20 MHz/s has been proved. Compared with the short rigid ultra-stable cavity stabilized lasers, this kind of lasers has significant benefits, such as: compact, no optical alignment, robust, tunable, lower cost and even lower thermal floor. It should be of use in many applications.

However, compared with the ultra-stable cavity stabilized lasers, this new type of lasers has several points to be improved. The most difficult one is the poor long term stability, which is caused by a high temperature coefficient of approximately ~10^{-5} /°C for SMF-28 fiber, and ~10^{-7} /°C for a low temperature coefficient fiber. In addition the vibration sensitivity of this laser is still more than 1 order in amplitude higher than the ultra-stable cavity laser. We also need to prove that the calculated thermal floor is accurate enough at very low Fourier frequencies.

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