An ultra-low frequency noise agile laser

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INTRODUCTION

Very low frequency noise laser sources are key elements of many applications, such as: atom or ion optical clocks [1, 2], ultra-stable microwave (MW) frequency generation [3], gravitational wave detection [4], ultra-stable optical frequency transfer [5], and so on…

The laser frequency-locking technique developed by Pound, Drever and Hall (PDH) [6] is widespread as the commonly used method of laser frequency stabilization on optical cavities, and it has been successfully demonstrated on lasers of various wavelengths. It led to a fractional frequency instability lower than 10^{-15} for 1 s averaging times and subhertz line-width [7]. This approach has intrinsically two weaknesses. First, it requires fine alignment of free-space optical components, tight polarization adjustment, and spatial mode matching. In addition, the cavity has to be housed in a high vacuum enclosure with thermal radiation shielding. This makes the system relatively expensive, bulky and fragile. The second weakness is that the PDH method does not allow tuning the laser frequency.

An alternative method is to use a two arm (Michelson or Mach–Zehnder) interferometer to measure the frequency fluctuations during a fixed time delay [8-11]. This method requires a relatively large arm imbalance to obtain sufficient frequency-discriminator sensitivity. Indeed, with a Michelson interferometer, the quality factor is proportional to the fiber delay. For example, using a 5km fiber delay line the quality factor of the interferometer is about 30 billions for a 1.55 μm wavelength laser, which is equivalent to the quality factor of a 10 cm Fabry-Perot cavity with finesse about 230 thousands. This stabilization technique allows a more robust, simpler, cheaper, transportable and frequency-tunable laser with low frequency noise.

In our experiment, we use the frequency shifted heterodyne Michelson interferometer to stabilize laser frequency. Since the laser frequency can be chirped by setting a frequency offset onto the demodulation signal, we call the laser an "agile laser".

OPERATION PRINCIPLE OF FIBER STABILIZED LASER & EXPERIMENTAL SETUP

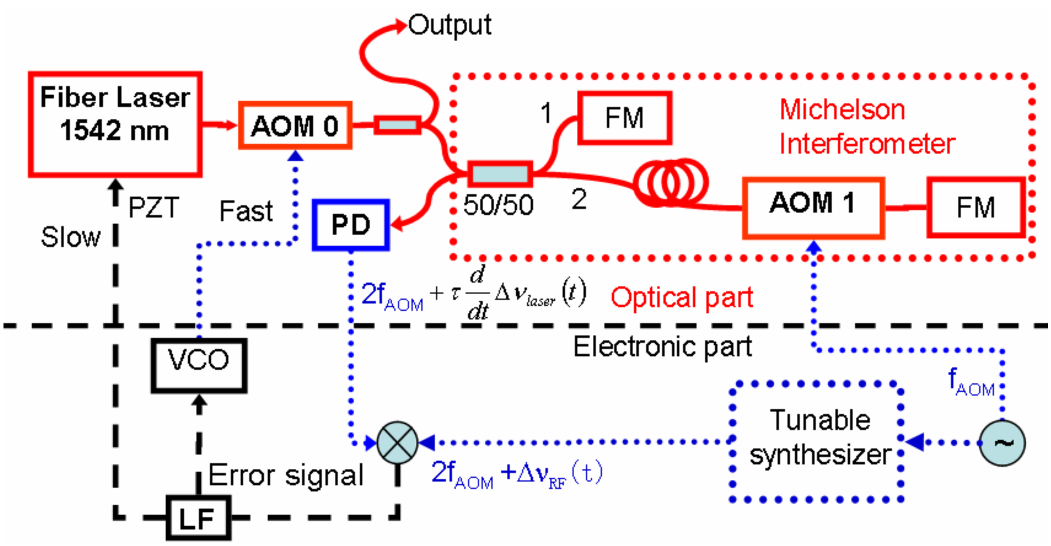

Fig. 1. Experimental setup frame scheme: VCO (Voltage Controlled Oscillator), AOM (Acousto-Optical Modulator), FM (Faraday Mirror).

Fig.1. shows the scheme of the agile laser, where the optical signals, RF signals and low frequency signals are drawn in red solid, blue dot and black dashed respectively. An acousto-optic modulator (AOM1) is placed into one arm of the interferometer and modulated by a 70-MHz RF signal. Consequently, the heterodyne detection signal is at 2fAOM1 (140-MHz) frequency. We use a home-made low phase noise tunable synthesizer providing a 2fAOM1 + $\Delta\nu_{RF}$(t) RF signal for demodulation. Successively, a Loop Filter (LF) converts the demodulated signal into laser frequency correction signals. These correction signals simultaneously act on a PieZo-electric Transducer (PZT) stretcher of the laser and a Voltage Controlled Oscillator (VCO), which drives AOM0. When the control loop is closed the frequency offset $\Delta\nu_{RF}$(t) will then induce a laser frequency change $\Delta\nu_{laser}$(t) given by

$$\Delta\nu_{laser}(t) = \frac{\int_0^t \Delta\nu_{RF}(t')dt'}{\tau}, \qquad (1)$$

This expression shows that a constant frequency offset $\Delta\nu_{RF}$ generates a linear laser frequency sweeping with chirp rate $\Delta\nu_{RF}/\tau$. . All interferometer components are pigtailed off-the-shelf, which makes the system alignment-free, simple and robust. The reference fiber is the Single Mode Fiber (SMF-28), which is widely used in telecom systems.

FIBER-STABILIZED LASER IN NON CHIRPED SITUATION ($\Delta\nu_{RF}$ = 0)

In non chirped operation, $\Delta\nu_{RF}$ is set to zero. The RF beat-note between the fiber-stabilized and a high-finesse cavity stabilized lasers described in [12] is frequency-to-voltage converted and analyzed by a fast Fourier transform analyzer.

The frequency noise PSD (red solid line) of the beat-note signal between the 2.5-km fiber-stabilized laser and a cavity-stabilized laser is shown in Fig.2a. Compared with the frequency noise (black dashed line) of two cavity-stabilized lasers, the frequency noise of the fiber-stabilized laser is at least as low as that of one cavity-stabilized laser for Fourier frequencies ranging from 30-Hz to 3-kHz. For Fourier frequencies lower than 30-Hz, the fiber-stabilized laser is only 10 dB noisy than the cavity-stabilized laser. In this range, we are probably limited by vibrations and temperature fluctuation (no vacuum and no servo of temperature in our assembly). Nevertheless, the performances in the decade 1 Hz-10 Hz have been improved by up to 10 dB compared to our previous results obtained with a 1-km fiber [13]. Anyway, over the range from 1-Hz to 3-kHz, the frequency noise PSD is well below 1Hz^2/Hz.

The instabilities are also measured by counting the frequency of the beat-note between the fiber-stabilized laser and the cavity-stabilized laser. The counter is a dead time free Π-type counter, which is equivalent to a phase recorder. The Allan deviation is calculated after removing a linear drift of less than 1.5 kHz/s. This deviation shown in the Fig.2b indicates the relative frequency fluctuation at corresponding integration time. It demonstrates that the fiber laser has a stability level about 10^{-14} in the range from 0.1-s to 1-s integration time.

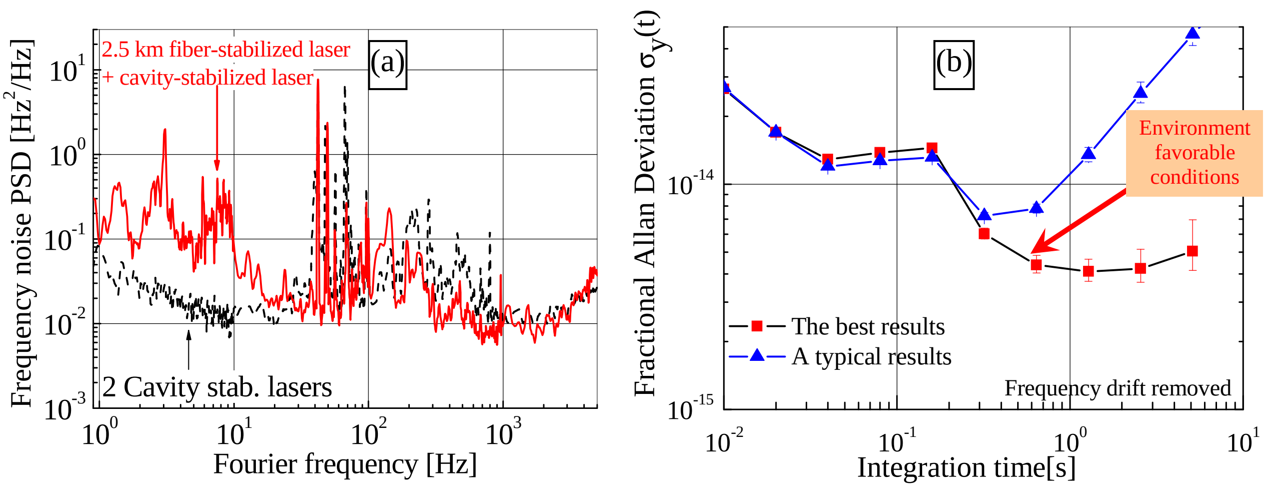

Fig. 2. Frequency noise and instability of the non-chirped laser.
(a) Frequency noise PSD of lasers beat-note between fiber-stabilized laser and an ULE-cavity stabilized laser (red solid line) and two ULE-cavity stabilized lasers (black dashed line).
(b) Instability of the non-chirped 2.5-km fiber-stabilized laser after removing a linear drift.

FREQUENCY SWEPT LASER ($\Delta\nu_{RF} \neq 0$)

One advantage of the fiber stabilized laser is the large range frequency tunability. Indeed, according to the equation (1), setting for example the frequency offset to 500 Hz allows to tune the laser frequency with the chirping rate of 20 MHz/s (for a 2.5 km-long fiber). In this case, the frequency noise cannot be simply measured with the same technique used for the non-chirped laser, because of the limited working range of the frequency-to-voltage converter (~1 MHz). Consequently, we use a second Michelson frequency-shifted interferometer with a 1-km fiber spool to convert the laser frequency noise into RF phase noise on the beat-note signal between the optical fields at the interferometer output. In this way, a linear optical frequency sweep is converted into a constant RF frequency shift. The measurement scheme is shown in Fig. 3a. The phase noise of the beat-note signal at the output of the measurement interferometer is evaluated with a standard phase noise measurement technique. We use a low phase noise quartz oscillator weakly phase locked on the RF output signal of the measurement interferometer (~1 Hz bandwidth). Thus, we obtain the phase noise at the output of the phase detector for Fourier frequencies larger than the control bandwidth which is measured using a FFT analyzer. The phase noise PSD is then converted into optical frequency noise PSD using the scaling factor $1/(2\pi\tau)^2$ .The results is shown in Fig. 3b for the chirping rate of 2 MHz/s.

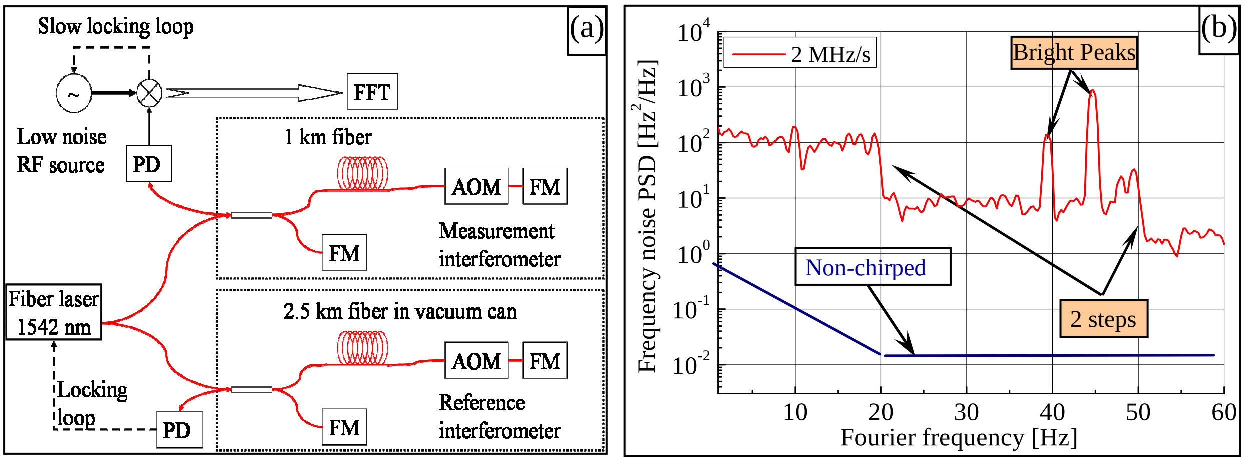

Fig. 3. (a) Scheme of the frequency noise measurement of a chirped laser using a second demodulation interferometer
(b) Frequency noise PSD of the laser at chirped rate of 2 MHz/s.

As can be seen in the Fig. 3b, the spectrum is significantly degraded with respect to the non-chirped situation and exhibit a quite peculiar shape characterized by two steps and several bright peaks. We attribute the bright peaks to localized stray reflections in the interferometers [14]. The steps are a clear sign of Rayleigh backscattering (RBS) in both the reference and measurement fibers. Indeed, the RBS beat with the signal from de delay line as the main signal from the short arm. We deeply investigate this effect theoretically in the case of chirped laser [14]. We demonstrate that the frequency noise due to RBS in one of the interferometers can be expressed by

$$\begin{cases} S_\nu(f) = A\dfrac{1}{(2\pi\tau)^2\nu'}, \; f \le \tau\nu' = \Delta\nu_{RF} \\ S_\nu(f) = 0, \; f > \tau\nu' \end{cases} \qquad (2)$$

where A depends on the parameters of the fiber and ν' is the laser tuning rate. The level and frequency width of the steps depend on the chirping rate, the delay time of each interferometer. We proved that the observed widths of steps match exactly the value expected from the equation (2) [14].

In order to remove to remove the first-order parasitic reflection effects, especially RBS effect, we adopt the single reflection immune configuration Fig. 4a. It's possible to eliminate this effect by distinguishing the main signal of the short arm from the first order reflection signal. Therefore, the introduction of a second AOM as shown in Fig. 4a., the frequency of signal at the interferometer output will be different to any beatnote signal relevant to the first order reflection signal.

To measure the frequency noise of the chirped laser with a 2-AOM configuration, which should be lower than the previous system, we compare the chirped laser signal with the cavity stabilized laser signal. The beat-note signal is recorded by a frequency counter with a gate time of 1 ms, and the frequency noise spectrum is obtained by fast Fourier transform of the counter samples. This frequency noise measurement method exhibits a lower noise floor than the previous double interferometer method. However, the spectral analysis range is limited to half of the counter gate time and the spectral power density is degraded by aliasing. Fig. 4b shows the laser frequency noise spectrum measurements.

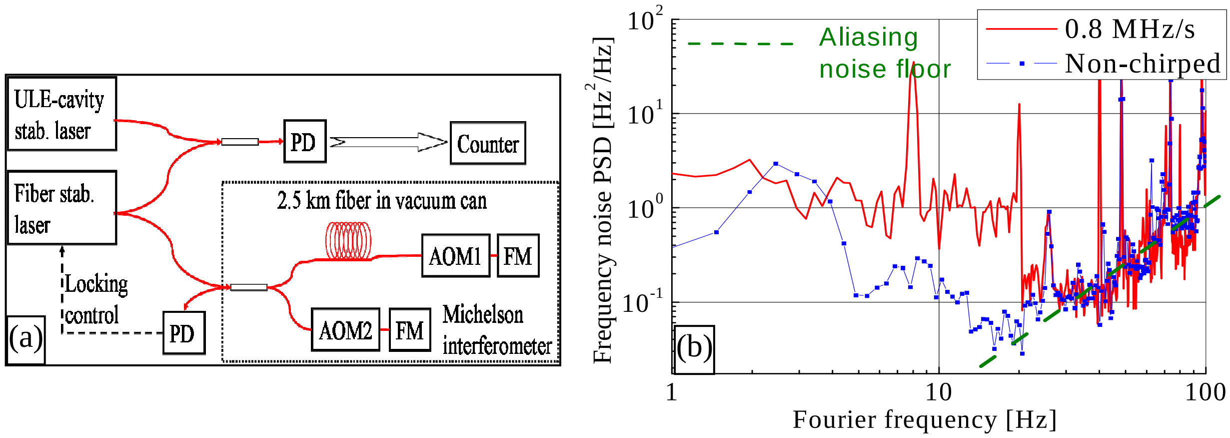

Fig. 4. (a) Enhanced Michelson interferometer scheme with single RBS immunity
(b) Frequency noise of single RBS suppressed fiber-stabilized laser for chirp rate of 0.8 MHz/s

The measurement noise floor is about 1/20 of the previous one. At Fourier frequency higher than $\Delta\nu_{RF}$, no additional noise is observed, this confirms our analysis. The spectrum still exhibits step. By analyzing the RF spectrum at the output of the interferometer, we found a 1~2% stray reflection from the long arm, which consequently generates a RBS signal traveling in forward direction. This RBS signal travels in the forward direction it is frequency-shifted by AOM1 before reflection by the Faraday mirror. It consequently contributes to the beat-note signal at $2(f_{AOM1}+f_{AOM2})$ frequency and induces a frequency noise given by Eq. 2.

LINEARITY OF THE CHIRPED FIBER-STABILIZED LASER

For an agile laser, the tuning linearity is an important feature [15, 16]. The chromatic dispersion of the fiber, parasitic reflections and the fiber delay fluctuations simultaneously degrade the laser tuning linearity.
We chirp the laser at a rate of 40.5 MHz/s over a 600-MHz range. In order to clearly demonstrate the chirp linearity, we removed the linear drift (laser drift) as the expected linear controlled ramp, from the recorded beat-note frequency samples. The peak-to-peak deviation is about 50 Hz (see Fig. 5a).

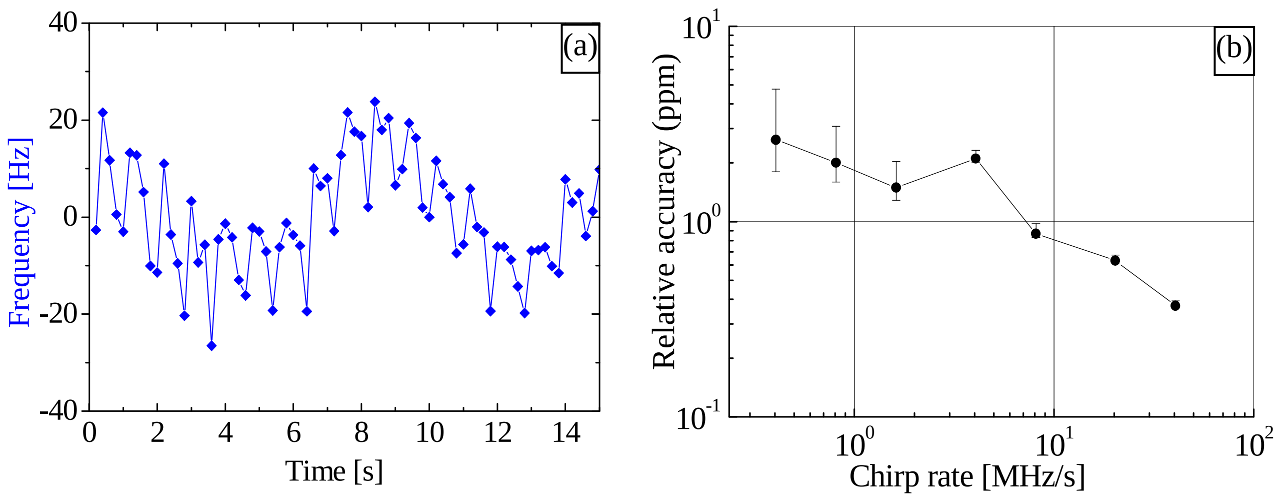

Fig. 5. (a) The beat-note between chirped laser and cavity laser and its fluctuations without the linear drift. (b) Chirp rate relative accuracy with respect to the chirp rate

In [14] we determined the relative non linear term due to chromatic dispersion and we showed that this effect is negligible in comparison with the residual fiber delay fluctuation due to temperature, vibrations and parasitic Fabry-Perot effect. We also evaluate the relative chirp rate accuracy with respect to the chirp rate. A calibration procedure is required to accurately determine τ. Then we chirp the laser at different rates ranging from 0.4 MHz/s to 40 MHz/s. The chirp rate error is the measured chirp rate by removing a linear frequency ramp calculated using the previously determined τ and $\Delta\nu_{RF}$. We found that beyond 10 MHz/s, the non-linear error is below 1 part per million (ppm) (see Fig.5b). More details are given in [14].

CONCLUSION

We have developed an agile laser with ultra-low frequency noise and high stability. This laser is frequency-stabilized onto a full fibered Michelson interferometer with 2.5 km fiber in the long arm. The use of a heterodyne detection configuration (AOM frequency shifter in one arm) allows the laser to be frequency-tunable without any fiber physical modification and in addition having a lower detection noise than a homodyne configuration.
The frequency noise power spectral density of this laser is comparable to that of an ultra-stable cavity stabilized laser at Fourier frequencies higher than 30 Hz. When it is chirped at a constant rate of ~ 40 MHz/s, the non-linearity frequency error is about 50 Hz peak-to-peak over more than 600 MHz tuning range. The frequency stability is about or better than 10^{-14} for integration times of 0.1 s ~ 1 s, when a linear drift due to controlled chirp and thermal drift of the reference fiber is removed.
We find that the Rayleigh backscattering is a significant frequency noise source. This noise level is inversely proportional to the chirping rate and the fiber length. After analyzing this effect both theoretically and experimentally, we put forward a technique to reduce this noise contribution. By adding a second AOM frequency shifter we are able to eliminate the first order Rayleigh backscattering effect. The 0.8 MHz/s chirped laser has a Rayleigh backscattering induced frequency noise of 1 Hz^2/Hz at low Fourier frequencies, which is due to the Rayleigh backscattering of ~1% stray reflections and definitely can be further reduced.

Since the laser has low frequency noise and is digitally tunable, it can be frequency-locked or phase-locked with low control bandwidth. As a first example, it can be stabilized to an atomic transition or other stable references to achieve a low noise laser frequency reference exhibiting a good long-term stability. As a second example, it can be used as a low noise optical tracking oscillator for low orbit satellite (~1000-km) optical coherent ranging and distance measurements [17]. We also foresee this type of laser as a low cost clean-up optical tracking oscillator in long distance optical frequency distribution over fiber links.

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